Psychological Monographs

General and Applied

No. 465
1958

Shure and Halstead

Vol. 72
No. 12

# Cerebral Localization of Individual Processes

by

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Price $1.50

Edited by Norman L. Munn

Published by The American Psychological Association, Inc.

# Psychological Monographs:

## General and Applied

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Vol. 72, No. 12 Whole No. 465, 1958

Psychological Monographs: General and Applied

# Cerebral Localization of Intellectual Processes[1]

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THE PROBLEM of localization of function in man's cortex was given its most succinct expression by Broca, one of the earliest and more eminently successful workers in this field; he urged workers to define the functions to be localized and to determine their localization. Since his dicta have been set forth, numerous investigators have sought to detect specific intellectual loss following lesions to the brain. After some nine decades of research since Broca's original discovery of a speech center in man, it has become painfully evident that his suggestions were more easily stated than implemented. The problem of localizing psychological functions in the cortex continues to be beset with many factual, methodological, and interpretive difficulties, and these problems are multiplied when man rather than lower animals is the subject of inquiry.

It has been argued by some investigators that the attempt to correlate mental processes in man with their anatomical and physiological substrata in the cortex is at present, and perhaps permanently and essentially, an insoluable quest. For how, it has been asked, can one hope (*a*) to localize functions which are themselves not yet clearly defined, (*b*) with the use of tests which are of questionable purity and variable consistency, and (*c*) in a cortex which may have been altered in an idiosyncratic manner by experience. These difficulties are further compounded in cerebral ablation studies where anatomic lesions generally involve a wide and frequently unknown amount of error. The extensive array of confusing and contradictory findings which have emerged from localization studies on man bears testimony of these difficulties and reinforces a skeptical outlook.

Whether there is a consistent syndrome of loss following the removal of frontal lobe tissue in man, and whether the removal of frontal lobe tissue entails a greater or different kind of loss than comparable removals of tissue in nonfrontal areas, is still to be answered to the satisfaction of a majority of workers in this area. With regard to the relationship of extensiveness of the lesion to behavioral loss, there is again little unanimity of agreement from experiment, although common sense and clinical findings have favored the belief that impair-

[1] The authors are grateful to Theodore Rasmussen, Burton L. Hoffman, and Duke E. Hanna of the Department of Neurosurgery of Billings Hospital at the University of Chicago and to members of the Department of Neurosurgery at the Illinois Neuropsychiatric Institute for their preparation of the operative sketches used in this study.

The authors would also like to acknowledge their appreciation to David J. Chesler and Norma Shure who have edited and improved the readability of the manuscript.

ment is proportional to the size of the lesions.

Theories and speculations relating to this wide array of fact have developed rather freely, and answers to the questions of localization of higher functions have literally covered all the possibilities that one might devise by conjecture unfettered by factual considerations. At one extreme are the theories which argue for a very fine division of the cortex with a corresponding distribution of psychological functions. On the other side are those which argue for the concept of the brain as a dynamic unitary organ with a corresponding diffuse representation of intellectual ability in the cerebrum. However, the meshing of theory and fact, even when the latter has been selectively chosen to support a particular theory, has rarely been close.

The present research represents an attempt to bring to bear some critical findings on the localization of higher functions in the cortex of man.

*Need for More Well-Designed Research*

Up to the present time there has been no single study which has utilized a large number of lobectomy patients and has attempted to appraise systematically the effects of size, laterality, and locus of lesion upon performance on a battery of quantitative behavioral measures, where the latter specifically have been designed to detect cortical lesions. Where large numbers of subjects have been used, evidence of anatomic specification of the lesion has been generally poor or lacking. Conversely, where more precise anatomic specifications have been available, as in many isolated case reports, behavioral investigations have been carried out on a qualitative basis and/or with different test batteries.

Even in those few studies where data of improved quality have been collected, defects in experimental design have occurred. In comparing subgroups of patients with lesions of different loci, there has been a failure to carefully balance out or evaluate the effect of one or more variables which appeared to selectively influence particular subgroups. Depending on the magnitude of such biasing effects, the results of these studies have been vitiated or materially weakened in their definiteness.

Where so many factors enter into the final performance score of an individual, and where so many errors and difficulties enter into the determination of the lesion, the expectation of findings indicating strict and precise parcellation of higher functions in the cortex, as with many motor and sensory functions, is unrealistic. Instead, one should anticipate that the alterations in "higher processes" resulting from similarly localized cortical lesions, even those presumably producing qualitative rather than quantitative changes, will show a wide range of individual differences in their manifest appearance and appraisal. The logic and facts supporting this argument have been reported elsewhere (45).

If the above conclusion is correct, it has important implications for the experimental testing of the localization hypothesis, especially when the ablation technique is used.

Since elimination or control of the many sources of error is impossible with human subjects, the methodology of studies of cortical mapping must include procedures to randomize such factors as might selectively influence a particular group.

Confronted with the complexity of factors in determining the consequences of serving transcortical associative fibers in rats, Lashley concluded:

> Direct control of all anatomic and behavioral variables is impossible, either in experimental studies or analysis of clinical material. The effects of interrupting transcortical associative connections can be estimated only by study of a series of cases large enough to permit the partialing out of different factors contributing to deterioration through comparison of the effects produced by various combinations and amounts of injury to different systems (32, p. 260).

What appears to be required is the selection of a group of subjects of sufficient size and composition that random effects can be balanced, and if possible, evaluated for their actual significance.

By including such methods in his experiments, Lashley has been able to demonstrate uniform trends and consistent results in spite of marked individual variations in his animal subject.

*Related Findings*

It is clearly difficult, if not impossible, to evaluate consistencies or determine the significance of apparently diverse findings where differences in populations, tests, and lesion specifications exist among the various reports. The summation or comparison of findings based on such data can clearly lead to questionable results. However, such findings, cautiously interpreted, offer the best sources available from which to infer the cortical representation of intellectual processes.

A number of these functional-anatomic relationships which bear on the present study and which received confirmation from a number of studies are summarized below. It should be noted that, while supportive studies are cited following each relationship reported, a number of clinical and experimental reports question their validity. For a detailed summary of the literature and an assessment of conflicting findings, the reader is referred to critical reviews by Klebanoff (27), Klebanoff et al. (28), Battersby (3), and Shure (45).

Summary of localization findings:

1. Patients with frontal lesions are subject to greater loss on tests requiring ability to abstract than are patients with nonfrontal lesions (15, 17, 18, 43, 44).

2. Patients with left hemisphere lesions are subject to greater loss on tests requiring ability to abstract than are patients with right hemisphere lesions (15, 18, 38, 39, 43).

3. Patients with left hemisphere lesions are subject to greater loss on linguistic or verbal tests than are patents with right hemisphere lesions (2, 38, 49).

4. Patients with left hemisphere lesions are subject to less loss on nonverbal, visual-motor tests than are patients with right hemisphere lesions (2, 38, 49).

5. Lesions anywhere in the cortex appear to produce an impairment in psychological vigilance[2] and on some immediate memory and new learning tests; this impairment appears to be more related to the size of the lesion involved than to its locus in the cortex (2, 38, 43).

6. The loss following frontal lobe lesions extends into functions beyond an impaired ability to abstract (17, 43, 44), and this impairment is not as widespread in nonfrontal cases. The studies reporting these additional losses have used such different procedures for assessing behavior, however, that the commonalities are not clearly apparent.

As will be noted, Propositions 1, 2, and 5 above were used as the basis for hypotheses in the present study. The limited range of functions covered by the test battery in the present study did not appear to allow for adequate testing of the remaining propositions. However, data relating to the other propositions are also reported.

Hebb and others have pointed out that those cases with least intellectual

[2] Under psychological vigilance are grouped those tests believed to reflect directly small variations of conscious awareness below the optimal level. Tests making demands upon temporal and perceptual integrative span and tests of new learning and immediate memory are used as measures of this dimension of behavior. Further exploration of the meaning of the term will be deferred until the discussion section.

loss appear to occur among patients with uncomplicated removal of tissue, as in cortical excisions for treatment of psychosis (40) and epilepsy (23). In contrast, studies of frontal lobe tissue removal which most clearly reveal psychologic loss were based on patients with tumor removals. From such facts, Hebb posits that it is not the removal of tissue as such, but rather the presence of residual malfunctioning tissue which accounts for the losses seen in lobectomy patients. However, in studies by Rylander (43), Halstead (17), and Teuber et al. (48), results were reported which were not consistent with the hypothesis that dysfunctioning tissue is the agent primarily responsible for the losses noted. The failure to find consistent patterns or amounts of loss in epileptic patients for whom dysfunctioning tissue is clearly a responsible agent also argues against Hebb's hypothesis. On the basis of their studies, McFie and Piercy (38), Busch (4), and Rylander (43) also seriously question the deteriorating influence on intellectual performances of increased intracranial pressure, a presumed sequelae of brain tumors.

While not designed to explore the problem of tissue deficit versus malfunctioning tissue, the present study provides some significant findings bearing on this question by comparing the performances of patients operated upon for removal of epileptogenic tissue with patients operated upon for tumors.

## Purpose

Lashley's suggestion for methodology, noted previously, is followed in this study. The problem of cerebral localization is approached by analyzing the behavioral deficit found in patients with excised cortical tissue.

The present research differs from earlier lobectomy studies by combining the following conditions in a single study:

1. Data were collected on 72 patients, a larger group than that utilized in any previous lobectomy study.

2. Consistent, objective criteria were used for evaluating the locus and amount of tissue removed from each patient, and these criteria made possible a quantitative index of the size of the lesion.

3. Patients showing a wide range of differences in the amounts of tissue removed were studied.

(These first three conditions permitted a test of the mass action hypothesis on a considerably more adequate and rigorous basis than was possible in previous studies using human subjects.)

4. The test battery employed was specifically designed for the detection of cortical lesions. The testing sampled a number of specific behavioral tasks and offered an opportunity to study a wide range of performances.

5. A Fisherian statistical design (9) made possible a quantitative analysis of the influence of three aspects of the lesion—locus, hemisphere, and size—upon the test performances. Each of these three descriptive components of the lesion was systematically evaluated both singly and in all possible combinations. Of major importance here is the fact that the significance of each of the three major effects was assessed by procedures in which the other two major effects were balanced for any influence they might exert.

6. Two additional variables—patient's age and interval of time between surgery and testing—were analyzed for any systematic relationship that might exist among them and the three aspects of the lesion mentioned above. These two variables were further analyzed for any direct relationship with test performances.

7. The influence on test performances of differences in the nature of the preoperative problem was appraised for nonfrontal cases. Among this group, a sufficiently large number of patients treated for removal of epileptogenic foci or scar tissue was available for comparison with patients whose preoperative condition presumably resulted in wider cortical disturbance.

In addition to the generally empirical intent of this study, two specific hypotheses based on earlier localization findings were tested.

*Hypothesis I*

The cortex of man is subject to the law of mass action. Impairment in performance on tests which demand psychological vigilance for their solution is proportional to the size of the lesion in each patient's cortex, irrespective of the site of the lesion.

*Prediction Ia.* There will be a significant positive correlation in a group of lobectomy patients between the amount of cortical tissue removed and impairment in performance on tests which measure psychological vigilance (see Footnote 2).

*Prediction Ib.* Lobectomy patients with large lesions will not perform as well on tests measuring psychological vigilance as will patients with small lesions. (Prediction Ib is obviously not independent of Prediction Ia.)

*Hypothesis II*

There is a differential importance of various areas of the cortex in the solution of problems requiring ability for abstraction,[3] such that: (*a*) lesions in the frontal lobes produce more impairment of this ability than lesions in the nonfrontal lobes, and (*b*) lesions in the left hemisphere produce more impairment than lesions in the right hemisphere.

*Prediction IIa.* Patients with lesions in the frontal lobes will not do as well on tests of abstraction as will patients with lesions in the nonfrontal lobes.

*Prediction IIb.* Patients with lesions in the left hemisphere will not do as well on tests of abstraction as will patients with lesions in the right hemisphere.

[3] The term abstraction is identical in meaning to Halstead's *A* factor. He defines abstraction as the "ability to comprehend recurrent similarities in the presence of dissimilarities and vice versa" (**17**, p. 67).

## Experimental Procedures

### *Test Procedures*

The tests employed have been reported in some detail in a major study by Halstead (**17**). A manual describing the entire battery and the details of its administration and scoring has been prepared by Halstead and White (**19**). For our present purposes it will suffice to give a brief description of each test used.

*Test I. Halstead Category Test.* This test was designed as a measure of abstraction and requires the ability to note essential similarities in the presence of apparent differences and vice versa. The test consists of a series of 208 stimulus figures presented in a serial visual exposure. Organizing principle such as "size," "shape," "color," etc., must be discovered. The score is in terms of the total number of errors.

*Test II. Halstead Flicker-Fusion Test.* A Type 631-B General Radio Strobotac is used as the source of variably intermittent, low intensity light. Critical-fusion frequency of each subject is measured in ten ascending trials. The mean value of the last five trials is the score.

*Test III. Average Deviation of Critical-Fusion Frequency.* The score is the average deviation of the last five trials in the preceding test.

*Test IV. Halstead Performance Test (Speed).* A modification of the Sequin-Goddard form board. The board is presented at an angle of 70° from the horizontal. At no time does the subject see the form board or blocks. The score is the total time for three trials: the first with the dominant hand only, the second with the other hand, and the third using both hands.

*Test V. Halstead Performance Test (Recall).* After completing the above three trials without

vision, the subject attempts to sketch from memory an outline of the board with the shapes and positions of the various blocks on the board. The number of shapes recalled represents the score on this test.

*Test VI. Halstead Performance Test (Localization).* The number of shapes accurately placed in the drawing made in Test V constitutes the score on this test.

*Test VII. Seashore Rhythm Test.* This test requires the subject to judge whether a second number of a pair of rhythmical tone patterns is the same as, or different from, the first number. The test consists of 30 pairs of such items. The raw error score is converted into a decile rank by reference to Seashore's norms for the general population.

*Test VIII. Speech Discrimination Test.* A modification of a test prepared by L. D. Goodfellow. It consists of 60 spoken speech nonsense syllables involving the double vowel *ee*. The subject selects the sound heard from four multiple choice variants printed on the test blank. The score on this test is the number of errors.

*Test IX. Halstead Finger-Oscillation Test.* This test measures how rapidly a subject can tap a small lever key with the forefinger of his dominant hand. A mechanical counter activated by the lever tabulates the total number of taps for each ten-second trial. The score on this test is the average performance of five trials.

*Test X. Halstead Time-Sense Test (Memory).* In this test the subject estimates a ten-second interval by starting and stopping an electric clock. This judgment is made without the aid of vision. The score on this test is the average deviation of 20 trials from the ten-second criterion.

*Test XI. Halstead Time-Sense (Vision).* This test is similar to the preceding test but is performed with the aid of vision of the clock. The memory trials of the preceding test are interspersed with the visual trials in the sequence VVMVMV. Each of these letters represents a series of ten trials. As with the above test, the score is the average deviation from the ten-second criterion, but in this case it is based on 40 trials.

*Test XII. Seashore Measures of Musical Talent.* The separate discrimination tests covered are those on pitch, loudness, time, timbre, rhythm, and tonal memory. The score on this test is the sum of the decile ranks on the full battery of the six subtests.

*Test XIII. Henmon-Nelson Tests of Mental Maturity.* This is a verbal, paper-and-pencil intelligence test which yields an intelligence quotient.

Special interests or difficulty in testing dictated the administration of the Wechsler-Bellevue or Stanford-Binet, rather than the Henmon-Nelson, to seven cases. While combining IQs based on different tests undoubtedly introduces an additional source of error, it was feared that their omission might introduce a similar bias, as these two tests are generally called for with individuals at rather low or above average levels of ability. Differences in intelligence between the various lesion groups were evaluated, both including and excluding the Stanford-Binet and Wechsler-Bellevue scores.

*Test XIV. Carl Hollow-Square Test.* In this test the subject is required to assemble into a square a number of blocks of various straightline geometrical shapes, each of which also has both right-angled and beveled edges.

*Test XV. Halstead Impairment Index.* This measure is derived from scores on the first ten tests in the battery. Each of these tests which falls below a critical value contributes 0.1 toward the index. The critical scores for each test are listed in Appendix A. An index of 1.0 reflects a maximum degree of loss. The index is calculated for all cases taking four or more of these tests. Only two cases for whom indices are calculated took only four tests.

The test scores for each subject are presented in Appendix B.

### *Selection of Subjects*

The patients were selected from the neurosurgical service of the Albert Merritt Billings Memorial Hospital of the University of Chicago and from the Illinois Neuropsychiatric Institute. All the patients studied underwent neurosurgical removal of tissue which was confined to either the pre- or post-Rolandic area of the cortex and to the right or left hemisphere. The specific reason for neurosurgery in each case, the date of operation, and the name of the neurosurgeon are listed in Tables A-H.[4] The reasons for neurosurgery were varied although the largest proportion of the cases was operated upon for removal of some form of cerebral tumor. Cases treated for psy-

[4] These tables have been deposited with the American Documentation Institute. Order Document No. 5730, remitting $1.25 for 35-mm. microfilm or $1.25 for 6 × 8 in. photocopies.

chosurgery were not included in this study. Thirty-seven of the cases were studied by Halstead in previous studies (**17**). To this group were added 35 additional lobectomy patients, to make a total of 72 cases.

*Specifications of the Lesion*

A diagram of the cortical lesion in each of the 72 cases is presented in Appendix C. The lesions were sketched on the Halstead Brain Lesion Chart (**16**), which permits the representation of the lesion as seen from four perspectives. For 57 of these cases, sketches were either made directly at the terminal stages of neurosurgery or reconstructed on these charts from drawings made at this time.

These sketches were then traced onto millimeter graph paper to estimate the size of the cortical lesion as represented on the Halstead Brain Lesion Chart. The number of square millimeters encircled by the tracings of the excised cortex was used as an index of the surface area of excised cortex for each patient. The "per cent surface lesion" estimate was obtained for each case by dividing the excised surface area obtained from the above procedure by the total number of millimeters covered by the four views of the cortical surface.

For 15 of the cases in the study, the sketches of the lesions were not prepared by the neurosurgeon either during or shortly following surgery. In an effort to utilize such cases in this study, two neurosurgeons were asked to prepare independent sketches of the operative lesion from data in the patient's medical file. The surgeon's operative notes, the pathology laboratory reports of the tissue removed at surgery, and postoperative X-ray findings were used in preparing these sketches. Cases were included in the study only if both neurosurgeons rated as "reasonably sure" or "confident" their reconstruction of the operative lesion, and if both estimates of the per cent surface lesion agreed in classifying each patient into the small or large lesion category.

The first criterion eliminated patients whose case folders failed to provide sufficient data for an accurate sketch of the lesion. Since the dividing point for the large and small lesion groups was chosen as 6.5 per cent surface lesion, the second criterion required that both estimates for any particular case be either above or below this value. The per cent surface lesion estimate which was used for these cases was the mean value obtained from the two sketches for each patient.

On the basis of the location from which the tissue was removed, plus the quantitative estimate of the size of the lesion, it was possible to classify each subject in terms of three independent variables:

1. *Per cent surface lesion.* Patients were divided into large and small lesion groups on the basis of the surface area of the cortical tissue excised. The cutoff point for classification into one or the other of the groups was the approximate median value for the entire group of patients, viz., 6.5 per cent surface lesion.

2. *Hemisphere.* Since only cases of unilateral removals were used in the study, lesions were classified as being in either the left or right hemisphere.

3. *Locus.* Similarly, since only those patients whose operative lesions were limited to either the pre- or post-Rolandic areas were included, the lesion in each case was classified as frontal or nonfrontal.

While it may have been interesting to carry our specification of the lesion further in terms of projection versus association areas or in terms of the various

TABLE 1

SIZE AND MEAN AGE OF EIGHT LESION GROUPS

| Lesion Group | No. of Patients | Mean Age |
|---|---|---|
| A. Left Nonfrontal Small | 12 | 32.5 |
| B. Right Nonfrontal Small | 11 | 31.8 |
| C. Right Nonfrontal Large | 7 | 32.1 |
| D. Left Frontal Large | 9 | 40.1 |
| E. Right Frontal Large | 10 | 36.8 |
| F. Left Frontal Small | 10 | 39.7 |
| G. Right Frontal Small | 6 | 34.7 |
| H. Left Nonfrontal Large | 7 | 32.4 |

Brodmann subareas, the methodology for mapping the lesions did not permit such determinations without a considerable margin of error. Analysis of the lesions was thus limited to the three dimensions stated above.

These three lesion dimensions each have two levels, and as a result, eight groups of patients ($2 \times 2 \times 2 = 8$) were formed. The number of patients in each group and their mean ages are presented in Table 1.

*Design of the Experiment*

The data were subjected to a $2 \times 2 \times 2$ Fisherian analysis of variance.

Table 1 shows that the number of patients in each of the eight groups varies from 6 to 12. To avoid the greatly increased computational problems involved in using unequal replications for each cell in the analysis of variance, an equal number of test scores were selected from each group. These were selected in the following manner. For the four small lesion groups, selection of test scores was begun with those patients having the smallest lesions and continued until the required number of scores for each cell was obtained. Conversely, for the four large lesions groups, selection of test scores was begun with those patients having the largest lesions and continued until the required number of scores for each cell were obtained. This procedure was used in place of a totally random selection of scores from each subgroup so as to maximize the differences in lesion size between the large and small lesion groups.

Since some of the patients were not given the full test battery, the number of test scores from each lesion group (replications) was as low as three for two of the tests in which the three-fold analysis of variance was carried out.

Bartlett's test for heterogeneity of variance (9) was used to determine when the variances of the test scores within each of the eight groups were significantly different from each other. For Test IX, the Bartlett test was significant and a simpler analysis of variance ($2 \times 2$) was made.

For three of the tests, Student's $t$ was used to evaluate the significance of the difference among the means of the three lesion variables. The $t$ tests were used when the number or distribution of subjects for a particular test was not suitable for an analysis of variance, or when the Bartlett tests were significant.

While such factors as age and the length of interval between surgery and testing were suspected to be significant variables influencing test performance, it was impracticable to include them as independent variables in a single factorial study.

As a measure of the period of time between dates of operations and testing, the time index was calculated by taking the reciprocal of the number of weeks which elapsed during this interval. These indices are cited in Tables A-H (see Footnote 4). Thus, a person tested four weeks following surgery would have a value of 1/4 or .25 as his time index. The reciprocal transformation maximizes the importance of small differences

in time which occur most directly after surgery and minimizes the importance of such changes with the later passage of time. The time-index scores would thus more closely accord with the observation that recovery is most marked in its early phases and tends to level off with the passage of time. For purposes of presentation, all time-index scores have been multiplied by the value ten.

Two procedures were adopted, however, to assess the influence of these factors. The age and time-index measures were evaluated by the analysis of variance and $t$ test procedures respectively (in the same manner as other tests in the battery). This analysis indicated the extent to which either of these variables was nonrandomly distributed as a result of sampling or hidden biases with respect to any of the dimensions of the lesion which were under study. For both age and the time-index variable, no significant differences were found for any of the three classifications of the lesion (see Tables 2 and 3). This fortunate result makes it highly unlikely that the findings pertaining to the effects of tissue removal on test performances can be attributed to either age or time-index differences among the eight groups of patients.

While the above procedure was important in demonstrating that none of the three aspects of the lesion under study was confounded by the effects of age or the time-index variable, the question of the direct influence of these variables on test performance is not answered. To provide information on this question, each variable was individually correlated with every test in the battery. These intercorrelations are presented in Table 4. Also included in this table are the correlations of each test in the battery with the per cent surface lesion estimate.

While the hypotheses stated earlier may not be confirmed and the evidence on which the predictions are based is not without interpretative ambiguity, complete reversal of the assertions is not seriously anticipated. Thus, although it is possible for patients with smaller lesions to show greater loss than patients with larger lesions, this alternative does not appear to meaningfully concern us. None of the studies investigating the relationship between size of lesion and performance has reported such reversals. Similarly, in those studies in which cases with frontal lesions have not been found to be more impaired than nonfrontal cases, on tests of abstraction, data in support of the reverse of Prediction IIa has not been found.[8] For this reason the one-tailed test appeared to be most appropriate in evaluating the predictions in this study. For the logic involved in the use of the one-sided versus the two-sided test of hypotheses, see Jones (26).

## Results

Tests used as measures of the same psychological functions are considered jointly; additional results are reported on a test-by-test basis. Statistical probabilities for all findings which exceed the .10 level in significance are noted, although only those findings which exceed the .05 level of probability are reported as statistically significant. Two-tailed tests are used in all instances except where the direction of results is predicted. In the latter case, $F$ tests, Student's $t$, and correlation coefficients are all evaluated for significance by appropri-

[8] A single study which is almost an exception to this statement is that by Teuber, Battersby, and Bender (48). However, the reversal they noted failed to reach the .10 level of statistical significance for tests of abstraction. The findings of this study are also open to an alternative interpretation (45, p. 136).

TABLE 2

ANALYSES OF VARIANCE *F* RATIOS FOR TEST BATTERY

| Sources of Variation | Test I | Test II | Test IV | Test V | Test VI | Test VII | Test VIII | Test IX[a] | Test X | Test XI | Test XII | Test XV | Age of Patients |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Locus | 2.054* | 1.762 | — | 5.060** | — | — | — | — | — | — | 3.198* | 11.810*** | — |
| $C_L$ Lesion | — | 3.062** | — | 1.368 | — | 2.343* | 3.293** | — | 1.069 | — | 1.470 | — | — |
| Hemisphere | 2.509* | — | — | — | — | — | — | 1.293 | — | 5.827** | 2.206 | — | — |
| $C_L \times L$ | — | — | 4.407** | 6.809* | 3.930* | — | 1.641 | — | — | — | — | — | — |
| $H \times C_L$ | 6.810** | — | — | — | — | 4.682** | — | — | — | 3.853* | 3.646* | 2.374 | — |
| $H \times L$ | 1.083 | — | — | 2.340 | — | — | 2.234 | — | — | — | 1.779 | — | — |
| $L \times H \times C_L$ | 1.349 | — | — | — | — | — | 2.564 | — | — | — | — | 1.803 | — |
| Number of Patients | 32 | 48 | 40 | 40 | 40 | 32 | 24 | 48 | 48 | 32 | 24 | 48 | 48 |
| Entries per Cell | 4 | 6 | 5 | 5 | 5 | 4 | 3 | 12 | 6 | 4 | 3 | 6 | 6 |

[a] A 2×2 analysis was carried out on this test.
* Significant between .10 and .05 levels.
** Significant between .05 and .01 levels.
*** Significant beyond .001 level.

ate one-tailed tests. Analysis of variance results (*F* ratios along with the size of the sample on which these were obtained) are summarized in Table 2. Table 3 contains similar information for those tests analyzed by Student's *t* test. Table 4 lists the correlation coefficients between each test and size of lesion, age, and time index.

*Abstraction*

Three tests in the battery are used as measures of abstraction: the Category Test (I), the Tactual Formboard (Recall) (V), and the Carl Hollow-Square Tests (XIV). The influence of locus, hemisphere, and the size of lesion is evaluated by *F* ratios in the analysis of variance for Tests I and V, and by *t* tests for Test XIV. The numbers of subjects used in these analyses are 32, 40, and 43 for Tests I, V, and XIV respectively.

One of the predictions with regard to performance on these tests was that patients with lesions in the frontal lobes would do more poorly than patients with nonfrontal lesions. The findings reveal that frontals are inferior to nonfrontals in performance on all three of these tests. These differences are significant beyond the .08, .02, and .003 levels of probability for Tests I, V, and XIV respectively. The .08 value obtained from the analysis of variance for Test I is based on only 32 of the 47 scores. A *t* test based on all of the available scores indicates that the mean score for the 21 frontals is significantly above the mean for the 26 nonfrontals, and that this difference is significant beyond the .01 level. No other test in the battery, taken by itself, differentiates frontal from nonfrontal cases at a statistically significant level.

The second prediction concerning performance on the abstraction tests was that patients with left hemisphere lesions would do more poorly than those with lesions in the right hemisphere. The findings show that right and left hemisphere groups do not differ significantly from each other on any of the three tests. The only indication of a trend in this direction is found for Test I. Patients with left hemisphere lesions are slightly more impaired on this test than patients with right hemisphere lesions. This difference is significant only beyond the .07 level of probability.

One further possibility needs to be explored. If both of the above predictions

TABLE 3

SUMMARIES OF *t* TESTS

| Variable | Lesion Group | *N* | Mean | *SD* | $M_1$-$M_2$ | *t* |
|---|---|---|---|---|---|---|
| Test III | Left | 35 | .797 | .555 | .035 | .243 |
| | Right | 34 | .832 | .621 | | |
| | Frontal | 33 | .755 | .766 | .114 | .780 |
| | Nonfrontal | 36 | .869 | .386 | | |
| | Large | 31 | .852 | .566 | .068 | .472 |
| | Small | 38 | .784 | .605 | | |
| Test XIII | Left | 20 | 83.85 | 18.05 | 10.79 | 1.816* |
| | Right | 25 | 94.96 | 20.31 | | |
| | Frontal | 22 | 89.64 | 19.73 | 5.29 | .882 |
| | Nonfrontal | 23 | 90.04 | 20.45 | | |
| | Large | 19 | 86.79 | 20.15 | 5.29 | .881 |
| | Small | 26 | 92.08 | 19.77 | | |
| Test XIII[a] | Left | 16 | 80.13 | 14.29 | 12.05 | 2.059** |
| | Right | 22 | 92.18 | 19.18 | | |
| Test XIV | Left | 18 | 100.89 | 21.66 | 1.57 | .254 |
| | Right | 25 | 99.32 | 18.15 | | |
| | Frontal | 17 | 89.65 | 17.03 | 17.08 | 3.028*** |
| | Nonfrontal | 26 | 106.73 | 18.70 | | |
| | Large | 17 | 88.71 | 19.47 | 18.64 | 3.381*** |
| | Small | 26 | 107.35 | 16.47 | | |
| Time Index[b] | Left | 20 | 1.793 | 3.285 | .609 | .673 |
| | Right | 20 | 1.184 | 2.368 | | |
| | Frontal | 20 | 1.340 | 2.508 | .297 | .327 |
| | Nonfrontal | 20 | 1.637 | 3.202 | | |
| | Large | 20 | 1.985 | 3.291 | .993 | 1.108 |
| | Small | 20 | .992 | 2.289 | | |

[a] Excludes the seven scores based on S-B or W-B tests included in the above comparison.
[b] Nonparametric tests yield similar results.
* Significant between .10 and .05 levels.
** Significant between .05 and .01 levels.
*** Significant between .01 and .001 levels.

are assumed to be correct, one might expect to find a significant *F* ratio for the "hemisphere × locus" interaction as a joint expression of both influences. That is, we might expect patients with left frontal lesions to be most impaired, patients with right nonfrontal lesions to be least impaired, and the left nonfrontal and right frontal patients to fall somewhere in between these two groups. This relative order in performance among these subgroups is not found for any of the three abstraction tests. Similarly, no significant *F* ratios for the "hemisphere × locus" interactions are found for the two tests where interactions are evaluated by the analysis of variance procedure.

Size of lesion is related to performance on all the tests of abstraction, although the relationship manifests itself somewhat differently in each of the three tests. On

TABLE

CORRELATIONS OF TEST BATTERY WITH AGE, TIME

| | | Test Indicator | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | I | II | III | IV | V | VI | VII |
| Age | $r$ | −.001 | −.235 | −.094 | .054 | −.142 | −.288 | −.162 |
| | $SE$ | .147 | .121 | .121 | .125 | .125 | .125 | .151 |
| | $N$ | 47 | 69 | 69 | 65 | 65 | 65 | 45 |
| | $p$[a] | — | .06 | — | — | — | .03 | — |
| % Surface Lesion | $r$ | .262 | −.312 | −.070 | .288 | −.219 | −.073 | .313 |
| | $SE$ | .147 | .121 | .121 | .125 | .125 | .125 | .151 |
| | $N$ | 47 | 69 | 69 | 65 | 65 | 65 | 45 |
| | $p$ | .08 | .005[b] | — | .03 | .08 | — | .02[b] |
| Time Index | $r$ | .272 | −.369 | −.076 | .159 | .021 | −.079 | .441 |
| | $SE$ | .154 | .141 | .141 | .143 | .143 | .143 | .156 |
| | $N$ | 43 | 51 | 51 | 50 | 50 | 50 | 42 |
| | $p$ | .08 | .01 | — | — | — | — | .01 |

[a] The $p$ values indicate the probability that $r$ differs from zero. Only $p$ values of .10 or less are presented.
[b] One-tailed tests were used to determine the significance level for those tests in which the direction of the correlations were predicted by hypothesis.

Test XIV, the large lesion cases are significantly more impaired than the small lesion cases. This difference is significant beyond the .002 level of probability. Evaluation of results on Tests I and V fail to reflect any difference between large and small lesion groups as such, but for Test I, the "hemisphere × area" interaction, and for Test V, the "area × locus" interaction are significant beyond the .03 and .02 levels respectively.

The correlations between size of lesion and performance scores on these tests similarly reveal a suggestive trend. The correlations for Tests I, V, and XIV are significant beyond the .08, .08, and .01 levels respectively.

In checking our own data to confirm Rylander's (43) reported relationship between performance on tests of abstraction and size of lesion for frontal lobe cases only, the interesting results in Table 5 were found. For all three tests, the correlations between size of lesion and test performance is larger for the frontal lobe cases than for the total group.

When the nonfrontal group is compared to the entire group, the reverse is the case. In the latter comparison, the correlations are all smaller than those obtained for the entire patient group. It thus appears that the major portion of the variance contributing to the correlation between size of lesion and abstraction test scores comes from the frontal lobe cases and that this relationship is markedly attenuated in nonfrontal cases. This same fact is brought out in compar-

TABLE 5

CORRELATIONS OF PER CENT SURFACE AREA OF LESION WITH SCORES ON THREE TESTS OF ABSTRACTION

| Lesion Group | Test I | Test V | Test XIV |
|---|---|---|---|
| Frontal & Nonfrontal (Combined) | .262 | −.219 | −.417 |
| Frontal | .349 | −.333 | −.693 |
| Nonfrontal | .201 | −.025 | −.211 |

Note.—The positive correlations for Test I and the negative correlations for Tests V and XIV reflect the fact that Test I is scored in terms of errors while Tests V and XIV are scored in terms of correct responses.

4

INDEX, AND PER CENT SURFACE LESION ESTIMATES

| Test Indicator | | | | | | | |
|---|---|---|---|---|---|---|---|
| VIII | IX | X | XI | XII | XIII | XIV | XV |
| −.099 | .058 | .007 | .073 | .048 | .095 | −.173 | .179 |
| .152 | .121 | .123 | .141 | .164 | .151 | .154 | .121 |
| 44 | 69 | 67 | 51 | 38 | 45 | 43 | 69 |
| — | — | — | — | — | — | — | — |
| .286 | −.003 | .212 | .285 | .049 | −.006 | −.417 | .106 |
| .152 | .121 | .123 | .141 | .164 | .151 | .154 | .121 |
| 44 | 69 | 67 | 51 | 38 | 45 | 43 | 69 |
| .03[b] | — | .09 | .05 | — | — | .01 | — |
| .436 | −.251 | −.130 | −.130 | .261 | −.274 | −.117 | .155 |
| .158 | .137 | .137 | .144 | .209 | .154 | .158 | .137 |
| 41 | 54 | 54 | 49 | 24 | 43 | 41 | 54 |
| .01 | .07 | — | — | — | .08 | — | — |

isons of the mean performance of the large frontal lesion cases with that of the small frontal lesion cases. The former are more impaired than the latter, as determined by *t* tests, and the differences between these groups are significant at the .05, .05, and .01 levels on Tests I, V, and XIV respectively.

Neither the time index nor age correlated with any tests of abstraction at a level which differed significantly from zero.

*Psychological Vigilance*

Three tests are used as measures of this function: the Critical Flicker-Fusion Test (II), the Rhythm Test (VII), and the Speech Perception Test (VIII). The influence of the locus, size, and hemisphere of the lesion on test performance is appraised for significance by the analysis of variance procedures. The total number of subjects used in this part of the analysis is 48, 32, and 24 for Tests II, VII, and VIII respectively.

The predictions for the measures of psychological vigilance hold that patients with large lesions would show greater impairment than patients with small lesions and that the level of performance on these tests would correlate significantly with size of lesion. The findings confirm the prediction that patients with large lesions perform more poorly than those with small lesions on all three tests. The *F* ratios for size of lesion are significant beyond the .05, .07, and .04 levels of probability for Tests II, VII, and VIII respectively. It is of interest that, of the 15 measures in the battery, only one other measure, the Carl Hollow-Square Test, reveals a significant difference between the mean performance of the large and small lesion group. Correlations between size of lesion and performance scores on Tests II, VII, and VIII are significant beyond the .005, .02, and .03 levels respectively. A breakdown of these correlations into frontal and nonfrontal cases does not reveal the consistent pattern found for the abstraction tests in Table 5. In fact, a reversal of this trend was noted for Test II. The correlation between test performance and size of lesion is −.312 for the total group of patients on this test. For 36 nonfrontal cases, the correlation for this test increases to −.483; this correlation coeffi-

cient is significant beyond the .01 level.

Right and left hemisphere patients do not differ significantly from each other, nor do frontal patients differ significantly from nonfrontal patients on any of the three tests. The *F* ratio for the "hemisphere × area" interaction is significant for Test VII beyond the .05 level. This is the only significant interaction for these three tests.

The correlations of the time index with each of these three tests are all significant beyond the .01 level. These findings assume added interest when it is discovered that none of the other measures in the battery correlated significantly with this index.

The correlation of age with Test II differs from zero beyond the .06 level. The other two tests failed to correlate significantly with age.

### Tests Involving Both Psychological Vigilance and Abstraction

The Tactual Formboard (Recall) (V) and Tactual Formboard (Localization) (VI) tests call for immediate recall of incidentally learned material, and as such, also would appear to classify as measures of psychological vigilance. This interpretation is reinforced by the fact that, in Halstead's factor analysis (17), both of these tests have loadings on Halstead's power factor (*P*) along with Test II, the Flicker-Fusion Test, which is used in this study as a measure of psychological vigilance. Halstead's *P* factor, in its operational definition, is closely related to psychological vigilance as defined in this study. This similarity is elaborated upon in the discussion section.

Tests V and VI also have sizeable factor loadings on Halstead's abstraction factor. Test V, which, it will be recalled, is used as a measure of abstraction, has a considerably larger loading on this factor than has Test VI. If it is assumed that these two tests each assess both of these functions, it might be anticipated that each will reflect, in some combined expression, the relationships found for each of the component functions when appraised individually. Since, from the findings just reported, locus of the lesion is related significantly to performance on tests of abstraction and size of lesion is related to performance on tests of psychological vigilance, it might be expected that the "locus × area" interaction will be significant for these tests.

Forty patients were used for the analysis of variance with each of these tests. The "area × locus" interactions show the most significant *F* ratios for each of these tests and are significant beyond the .02 and .06 levels for Tests V and VI respectively. In keeping with expectations, Test VI, which has a smaller loading on Halstead's abstraction and power factors than Test V, also has the less significant interaction term of the two tests. The other findings for Test V already have been reported and will not be repeated here. None of the other *F* ratios testing the importance of hemisphere, area, locus, or interactions of these variables are significant for Test VI. The correlation of age with performance on Test VI differs significantly from zero beyond the .03 level of statistical probability. This is the only test in the battery which showed a statistically significant correlation with age. The time index is not correlated with Test VI at a level significantly different from zero.

#### *Other Test Measures*

The analysis of the other tests in the battery are carried out with purely empirical intent and without specific hypotheses in mind. However, these tests also served as comparison measures in

that they presumably did not involve the two previously discussed functions to any sizeable extent, and as a consequence, findings for these tests could be contrasted with the results already reported. Only those findings of statistical significance or borderline statistical significance are presented.

*Impairment Index (Test XV).* Forty-eight cases were used in the analysis of variance procedures for this measure. Of the seven *F* ratios tested, only that for locus is significant. Cases with frontal lesions are more impaired than those with nonfrontal lesions and this difference is significant beyond the .001 level. Thus the Impairment Index is by far the most sensitive indicator in the battery for discriminating lesions in the frontal lobe from those in the nonfrontal lobes. No other relationships between the index and the other measures are significant.

*Intelligence Quotient (Test XIII).* The IQ of 45 patients, 38 based upon the Henmon-Nelson Test and 7 on the Wechsler-Bellevue and Stanford-Binet, were analyzed by *t* test. The mean IQ of the 20 patients with left hemisphere lesions is 83.85 and that of the 25 patients with lesions in the right hemisphere is 94.64. The *t* ratio for this difference is significant beyond the .08 level. Frontal-nonfrontal and large-small lesion comparisons do not reveal any significant differences. The correlation of IQ with the time index is significant beyond the .08 level. There was no relationship of statistical significance or borderline significance between IQ and size of lesion or age.

When only IQs derived from the Henmon-Nelson Test are evaluated by the *t* test, the difference between left and right hemisphere cases becomes significant beyond the .05 level. The mean for the left-sided cases is more than 12 IQ points below that obtained for the right-sided cases.

*Tactual Formboard (time) (Test IV).* An analysis of variance, using 40 subjects, was made. The *F* ratio for the "hemisphere × area" interaction term is significant beyond the .05 level. The correlation of test performance with area is significantly different from zero beyond the .03 level. No other findings of statistical significance emerge for this test.

*Time Sense Visual (Test XI).* Thirty-two subjects were used in the analysis of variance. Patients with left hemisphere lesions are more impaired than those with right hemisphere lesions. The *F* ratio for hemisphere is significant beyond the .04 level. This test is one of two in the battery which differentiate right and left hemisphere groups at a level of statistical significance. The "hemisphere × area" interaction for this test is also significant beyond the .07 level of probability.

Four tests fail to demonstrate any statistically significant relationships either in the analysis of variance procedures or the correlational analysis. Findings of borderline significance are reported.

*Critical Flicker Fusion Test (Deviation) (Test III).* Variance of the raw test scores within the eight lesions groups is significantly heterogeneous and remains so, even following two transformations of the raw scores in an attempt to reduce this variability. For this reason, the analysis of variance is not used. The differences in mean performance between large and small lesion groups, between right and left hemisphere groups, and between frontal and nonfrontal groups were evaluated by *t* tests.

No significant or borderline significant differences were found.

*Tapping Test (Test XI).* The correlation of test performance with the time

index differed from zero beyond the .07 level.

*Time-Sense Memory (Test XI).* The correlation of test performance with size of lesion differed from zero beyond the .09 level.

*Seashore Measures of Musical Talent (Test XIII).* Twenty-four patients were used in the analysis of variance. Frontal patients were slightly more impaired than nonfrontals. The *F* ratio for locus was significant beyond the .09 level. The *F* ratio for the "hemisphere × area" interaction was beyond the .08 level of statistical significance.

*Nature of Preoperative Lesion*

Cases treated for removal of epileptogenic foci and scar tissue (*E* cases) were compared with those cases treated for removal of tumors, abscesses, and cysts (*T* cases). The latter group presumably represented patients with more widespread cortical involvement than the former group. Comparisons were limited to patients with nonfrontal lesions as there were too few frontal patients treated for epileptogenic foci to carry out a similar analysis on this group.

Student's *t* tests were carried out on all tests to evaluate the significance of differences in mean scores between the E and *T* groups. Test XIV was the only test in the battery for which the *E* group's mean score was significantly above that of the *T* group. This difference was significant beyond the .02 level. The chance probability of obtaining at least one significant statistic at this level of confidence is .261.

## Discussion

*Abstraction*

Although definitions of abstraction vary, they usually include the ability to note common elements in miscellaneous stimuli, or conversely, the ability to perceive the member of a group which does not have the properties common to the other members. Many definitions have also included the ability to shift voluntarily from one aspect of a situation to another.

The three tests used as measures of abstraction in this study have been operationally defined in terms of their significant loadings on Halstead's *A* (abstraction) factor. Halstead described his *A* factor in essentially the same terms as used in the above definitions (**17**).

The concept of abstraction has been given broader theoretical significance by Goldstein and his colleagues (**12, 13, 14**). The present research will be confined to the problem of localization of abstraction in the cortex and will not concern itself with an analysis of the behavioral demands involved in this function.

*Importance of Frontal Lobes*

The present study strongly confirms the hypothesis that the capacity for abstract thought is more readily impaired by frontal than by nonfrontal lesions. Although a number of behavioral functions are appraised by the test battery, only the three tests measuring abstraction, and the Impairment Index discussed below, are differentially impaired by lesions in the precentral and postcentral areas.

The differences in performance between the frontal and nonfrontal cases do not appear to be attributable to the influence of hemisphere and size of lesion, as these factors are balanced and assessed for significance. Similarly, age differences do not appear to account for the findings. Although the mean age difference between frontal and non-

frontal patients is almost six years, it is not statistcially significant. In addition, age fails to correlate significantly with any of the three measures of abstraction. These findings suggest that the slightly greater age of frontals over that of nonfrontals does not account for the differences between these groups.

*The Significance of Residual Malfunctioning Tissues*

One further issue needs to be examined before the frontal lobes are assigned central significance in abstract thinking. Can the differences found be attributed to a greater incidence of residual pathological tissue in frontal than in nonfrontal cases? On first appraisal, this hypothesis is compelling since it fits well with two observations. First, there is a much higher proportion of patients treated for epileptogenic foci and scar tissue removal (*E* cases) among the nonfrontals than among the frontals. Since little secondary cortical damage is present preoperatively in *E* cases, they presumably have a greater opportunity for clean surgical removals than do patients treated for conditions like tumors, which presumably produce more widespread disturbances (*T* cases). Second, as has been suggested elsewhere, there is a greater possibility for secondary unilateral and bilateral involvement in frontal than in nonfrontal tumor cases.

To return to the first point, for the three abstraction tests, the scores of the nonfrontal *E* group are consistently above those of the nonfrontal *T* group, whose scores, in turn, are consistently above those of the frontal lesion cases. It thus appears that, for tests of abstraction at least, both locus of the lesion and the nature of the preoperative problem contribute to the variance of the frontal-nonfrontal differences reported. Caution, however, must be used in interpreting the differences found between the *E* and *T* groups.

There is only one significant difference between nonfrontal *E* and *T* cases for the entire test battery. As noted previously, the likelihood of obtaining at least one significant difference at the .02 level of confidence for 15 tests is .261. Hence, there is some danger in assuming this single significant difference, obtained for Test XIV, to be reliable. Furthermore, the *T* cases are, on the average, over one-third larger in lesion size than the *E* cases. This confounds the interpretation of any differences found between these groups. Thus, even if it is assumed that the difference obtained is not due to chance, one is still faced with determining whether it is lesion size or a unique difference between the *E* and *T* groups which is responsible for the difference.

If it is legitimate to assume that the *E* cases represent patients with a minimum of residual malfunctioning tissue, while the *T* cases represent the opposite situation, as has been suggested by Hebb and others, the conclusion seems warranted that the presence of dysfunctioning tissue in the nonfrontal *T* cases is not associated with significantly greater impairment than that found in nonfrontal *E* cases with a minimum or absence of residual dysfunctioning tissue. This was the case for 14 of the 15 tests in the battery. For one test, XIV, the data are ambiguous, but it appears that the nature of the preoperative problem may contribute significantly to the test's variance. In either event, the greater proportion of *E* cases among the nonfrontals cannot exclusively account for the differences in performance on abstraction tests between the frontal and nonfrontal

groups. This finding does not support the assumptions made by Hebb and others regarding the overriding, primary importance of residual malfunctioning tissue as the responsible factor in accounting for the loss following cortical excisions.

The second explanation holds that the differences between frontal and nonfrontal cases may be accounted for by the greater likelihood of widespread secondary damage in the frontal than in the nonfrontal cases. If this explanation is correct, it may also be assumed that the size-of-lesion estimates based on the amounts of tissue removed from the *nonfrontal* areas would be a more accurate approximation of the total lesion present in the cortex than would be the size estimates of *frontal* lobes lesions. This probably would be so because widespread secondary involvement need have little relationship to the amount of cortex which is directly involved and excised. Since the magnitude of correlations is reduced when a greater proportion of error enters into either of the two variables being correlated, one might expect the correlations between size of lesion and test performance to be lower in the frontals than in the nonfrontals. However, the converse is the case for all the tests of abstraction.

The above explanation also is not supported by the oft-quoted observation that neurosurgeons are more apt to leave residual malfunctioning tissue in the nonfrontal cortex, for fear of impairing vital sensory functions, than in the frontal lobes. However, it may be argued that tissue damage is correlated with the extent of measured lesion. If so, it is not understandable why the correlations of extent of lesion with tests of abstraction should be greater in frontals and less in nonfrontals unless there is, in fact, a difference in the importance of these two areas.

One final comment may be made with respect to another prediction offered by Hebb in discussing his malfunctioning tissue hypothesis. He has reported that the size or concentration of a pathologic lesion is not a safe guide to its importance in producing symptoms (23). If Hebb implies that the margin of error in predicting impairment from the size of a lesion in a particular case is considerable, we must agree with him. However, if his statement implies that there is no relationship between size of lesion and test performance, then the present findings contradict this interpretation.

The findings point to the following conclusions: (*a*) The greater impairment in abstraction found in frontal than in nonfrontal patients is not primarily due to differences in the incidence of malfunctioning tissue in these two groups. (*b*) There is no clear cut evidence that nonfrontal *E* and *T* cases, who presumably differ in amount of pathologic tissue remaining in the cortex, show significantly different behavioral impairment. (*c*) The malfunctioning tissue hypothesis leads to predictions which are not consistent with findings reported in this study.

### *Mass Action Within the Frontal Lobes*

Of equal importance with the demonstration of regional localization of abstraction ability are the findings which indicate that performance on all three abstraction tests is related to the amount of tissue removed from the frontal lobes. The correlation attains the relatively high value of $-.693$ for one of these tests. Considering the limited accuracy of the per cent surface lesion estimates and the probably logarithmic relationship between size of lesion and impairment, this

coefficient offers a striking indication of mass action within the frontal region of the cortex.

The importance of size of lesion as a critical factor in accounting for the loss in abstraction in frontal lobe patients confirms Rylander's findings (43) and indicates one possible basis for the failure of some studies to detect this impairment in frontal lobe cases, namely, the selection of cases with small lesions.

*Hemisphere Differences*

The findings fail to support the hypothesis of a hemisphere difference related to abstraction ability. The mean performance of the left and right hemisphere groups were almost identical on two of the three abstraction tests (V and XIV) which involve visual-motor performance. It was only on the Category Test, which demands a "logical-verbal" approach, that patients with left hemisphere lesions were somewhat more impaired than those with lesions in the opposite hemisphere. This test is also the only one of the three abstraction tests which has a significant loading on Halstead's *C* factor. An hypothesis which immediately suggests itself is that it is not the abstraction components which are related to hemisphere, but rather the language and symbol manipulation involved in some abstraction tests. The relationship between the *C* factor and left hemisphere lesions is further explored in discussing the findings on hemisphere dominance.

*Psychological Vigilance*

In a formulation by Head (21), the concept of vigilance refers to the general physiological efficiency of the central nervous system. He states that, at its optimal level, the healthy organism is characterized by a state of being fully awake —a clarity and vividness of attention and alertness. As vigilance is lowered, attention becomes impaired, concentration becomes more difficult, and feelings of drowsiness or fatigue are more in evidence. Head does not speculate about the mechanism underlying vigilance, although he indicates that it varies with structual changes in the central nervous system and under the influence of drugs and anesthetics.

Lashley (34) offers a similar formulation based on his early findings with rats and on the reports of others on human brain injury. He postulates a mechanism distributed throughout the cortex, and suggests that lesions irrespective of locus may lower the general excitability of the brain in proportion to the mass of cortical tissue destroyed.

More recently, Landis, Zubin, and Mettler (30) characterized the "dull or sleepy" reaction which they saw during the first postoperative month in their topectomy and lobotomy patients as a loss in vigilance. They attributed this transient behavior to the immediate effects of surgery and their physical sequelae on the efficiency of the nervous system.

While many tests reflect the marked lowering in consciousness which may influence the entire range of behavior, a number of tests appear to be particularly sensitive to small shifts in this dimension of behavior:

1. Minimal variations in psychological vigilance, or the degree of conscious awareness, appear to be reflected in tests making demands upon the temporal and perceptual integrative span as measured in the Critical Fusion-Frequency and Dynamic Visual Field tests of Halstead's *P* factor (17). Halstead pointed to the possible similarity between his *P* factor, based on such tests, and Head's and Lash-

ley's concepts in their earlier writings.

2. Alterations in the working level of consciousness are also reflected in tests of new learning and tests measuring the adequacy of immediate recall or recognition of a number of discrete stimuli when these are presented for short time intervals (**5, 42**).

It is appropriate to note at this point that Halstead's *P* factor, in its operational meaning, is almost identical to psychological vigilance as here defined. However, in his earlier work, Halstead related the "working level of consciousness" to his *C* factor. In describing the latter, he stated: "It reflects the span of attention that is either operative or potentially operative in exploring the psychologically 'new' " (**17**, p. 96). Halstead accordingly classified under his *C* factor tasks of new learning and immediate memory along with tests of old learning and remote memory.

The essence of his *C* factor, however, appears to be related closely to the organized nature of earlier learning and experience. A number of facts argue against the inclusion of immediate memory and new learning tests in this factor, and suggest instead that these tests be combined with those of the *P* factor as measures of psychological vigilance:

1. Old learning and new learning have been distinguished in a number of factorial studies of intelligence (**5, 10, 25**) and have been demonstrated to vary independently and differently under conditions of anxiety (**41**), anoxia (**17**), electroshock (**8**), and aging (**22**).

2. Anoxia, when it lowers the critical fusion frequency, results in impairment in immediate memory, as seen in lapses of memory for details, while at the same time leaving old learning relatively unaffected (**17**).

3. As already noted, Tests V and VI, which have a significant and borderline significant loading respectively on the *P* factor, measure incidental new learning.

On the basis of the above findings and rationale, three tests, the CFF (Test II) and two immediate memory tasks, Tests VII and VIII, were selected to reflect small variations in level of psychological vigilance below its optimal level.

The findings for these tests support the predictions made earlier. With the exception of the Carl Hollow-Square Test, these three tests were the only one in the battery for which a significant difference between mean performance of the large and small lesion groups was found. All three tests also correlated with size of lesion estimates at levels significantly different from zero. Unlike scores on tests of abstraction, scores on tests of psychological vigilance were not related to the location of the lesion, although findings for Test VII showed a significant "area × hemisphere" interaction.

The findings for Tests VII and VIII agree with those of McFie and Piercy (**38**). Tests of immediate memory are primarily related to size rather than to locus of cortical lesion.

These three tests also covary in another unique manner and are the only tests in the battery to do so. In spite of differences in recovery rate, in preoperative problem, and in amount and location of excised tissue, correlations between the time index and the three tests differ from zero beyond the .01 level. Since the time index is the reciprocal of the length of the interval between surgery and testing, this finding indicates a reduction in functioning on tests of psychological vigilance which is greatest immediately after surgery and which follows a positively decelerating recovery rate with the passage of time. This find-

ing is similar to the observations of Landis et al. (30) which they classified as a reduction in vigilance.

This finding appears to reflect the fact that, in the period immediately following surgery, there is a temporary increase in the extent of cortical lesion as a result of such factors as intracerebral pressure, edema, and trauma to neighboring tissue. Many of these influences are reversible and probably diminish as a negatively de-accelerating function of time. These phenomena suggest that the time index acts as a crude indicator of the size of the temporary lesion or disturbance in the cortex. Thus, those cases tested shortly after operation appear to have the largest temporary lesions; those at the longest period from the date of their operation would have the smallest temporary lesions. These temporary lesions exist alongside the permanent ones resulting from the removal of cortical tissue.

The significant correlations of all of the tests of psychological vigilance with both the lesion estimates and the time index suggest that psychological vigilance is impaired in proportion to the amount of cortical tissue which is removed and/or left temporarily dysfunctioning. Before we go on to explore some of the possible explanations for these relationships, one issue deserves consideration.

*Magnitude of the Correlations*

There may be some question whether the correlations in the present study are sufficiently high to be indicative of a mass action relationship. Although statistically significant, the correlations are below those obtained by Lashley (31) in his mass action findings. There are a number of reasons, however, why the correlations between the performance and size of lesion obtained in this study would not be as high as those obtained by Lashley. The first, and probably most important, factor is that Lashley produced lesions in some of his rats which are more than two times greater than the largest per cent surface lesions in this study. The reduction in range of this variable would attenuate the magnitude of the correlations. Second, the correlations obtained in the present study are calculated over that range of values where the relationship between the variables is smallest in magnitude, since the relationship between impairment and size of lesion appears to be a logarithmic one (33). Finally, many of the factors in cortical studies on lower animals cited by Harlow (20) would depress the correlations in human studies below those found in the animal studies. In view of the many factors which operate to reduce this relationship, the emergence of significant correlations for all three psychological vigilance tests suggests a relationship comparable to the one obtained by Lashley.

*Alternative Explanations of the Correlations*

The correlations between psychological vigilance test scores and size of lesion might conceivably arise from a number of possibilities. Four of these are reviewed with regard to their tenability in the light of data found in the present and related studies.

1. *Proportionate Malfunctioning Tissue Hypothesis.* One explanation of the correlations between size of lesion and tests of psychological vigilance would attribute the relationship to persistent *postoperative* tissue disturbances which are proportional to the amount of tissue removed. The arguments against this hypothesis are similar to those discussed

previously in evaluating the influence of residual malfunctioning tissue on the abstraction test findings. Since differences in the presumed extensiveness of *preoperative* cortical disturbance is found to be unrelated to differences in impairment for the three psychological vigilance tests, it seems unlikely that postoperative disturbance is a major factor accounting for the correlations. This is not to deny, however, that malfunctioning tissue, especially if it increases the degree of hypersynchrony of brain rhythms, may increase impairment in a number of cases. Hebb's insistence that the size of a pathologic lesion is not an index to its capacity for producing impairment is also difficult to reconcile with this hypothesis as an explanation for the correlations.

2. *Critical Area Hypothesis.* If psychological vigilance is supported by a critical area in the cortex, then the greater impairment of this function in cases with larger lesions might be attributed to the greater likelihood that large lesions rather than small ones would involve this area. However, the selection of cases with lesions limited to one of the four quadrants of the cortex tends to rule out this interpretation.

3. *Mass Action via Transcortical Integration.* Perhaps one of the most compelling hypotheses for the correlations is the one offered by Lashley to explain the correlations between size of cortical lesion and maze performance which he found in his earlier studies of rats. He concluded that the learning and retention of mazes was subject "to a law of mass action whereby the efficiency of performance of an entire complex function may be reduced in proportion to the extent of brain injury within an area whose parts are not more specialized for one component of the function than for another" (**31**, p. 25).

Later studies by Lashley himself, however, indicated that separation of each adjacent pair of achitectronic fields by long incisions through the cortex is followed by normal maze performance by some rats. He found no evidence of impaired performance attributable to the interruption of transcortical connections. He concluded, "There appears to be no such elaborate system of transcortical associative fibers as would be required for direct integration of the various sensory and motor fields" (**32**, p. 274).

More recent work by Lashley et al. (**35**) and findings by Sperry and his co-workers (**46, 47**) reinforce the conclusion that mass action findings cannot be explained by spread of excitation along corticocortical pathways by way of either specific nerve impulses or conduction of molar electrical field currents.

4. *Mass Action via Subcortical Integration.* Recent neurophysiological findings (**37**) have disclosed that, in addition to the classical, specific sensory pathways from the thalamus, there exists an unspecific afferent system, frequently referred to as the reticular activating system (RAS), which projects diffusely over the entire cortical mantle and in the main to the associational areas of the cortex. It has been demonstrated that electrical stimulation of the reticular formation and of the nonspecific pathways of this system, which fan out from the thalamus to the cortex, produces a widespread "activation" or desynchronization of the EEG. The latter refers to the appearance of fast, low amplitude rhythms in the EEG, and paralleling these changes in the EEG, a behavioral change to an aroused or an alerted state. What is critical from our standpoint is that ap-

parently any sensory stimulus or internally evoked thought process has the capacity to excite this system and to arouse and maintain a high level of cortical activation, and this is, in fact, the manner in which this system operates in the normally alerted waking state.

It has also been demonstrated that the lesions to the RAS characteristically produce a state of lowered behavioral vigilance or somnolescence, along with changes in the EEG from fast, low amplitude rhythms to slow, hypersynchronous activity.

In the study cited previously (**32**), Lashley concluded that thalamic degeneration subsequent to cortical incisions was sufficient to account for his earlier mass action findings. Detailed analysis of the lesions showed that impairment in learning and retention in his rats was directly proportional to the deterioration which was found in the thalamus.

Since lesions located almost anywhere in the cerebral cortex interrupt RAS projection and corticofugal fibers, it must be expected that patients with cortical lesions in the present study undergo a comparable degeneration of thalamic nuclei with resulting partial interruption of the diffuse thalamo-cortical system.

The inverse relationship between size of lesion and performance on psychological vigilance tests may thus be interpreted as due to a reduction in the number of functional pathways of the RAS which is roughly proportional to the size of the lesion. It is proposed that this relationship would hold for removal of tissue from any area of the cortex, attenuated only by local variations in the density of corticofugal and diffuse afferent projections of this system to various areas of the cortex.

Thus, the brain, with cortical lesions to the RAS, suffers from a reduction in the total cortical afferent influx and corticofugal feedback which normally maintains asynchronous brain rhythms and a high level of conscious awareness.

Cortical lesions appear to leave the cortex less capable of resisting the induction of a central state leading to lowered awareness. Hebb has indicated that, "The establishment of hypersynchrony, due to *any* cause, would provide a pacemaker, as it were, that would tend to pick up any neurons that are not incorporated in assembly activities and so substitute the 'intrinsic' organization of cortical activity for the diffuse organization of the normal waking state" (**24**, p. 273).

Thus, incoming afferent stimuli or corticofugal feedback is necessary to break up any existing hypersynchronous pattern and produce a return to a normal level of adaptive conscious activity (**1, 11, 24**), but it is precisely such stimulation which is reduced by cortical lesions.

Considerably before the unspecific afferent system was discovered, Kleitman (**29**) emphasized the importance of both sensory and cortical influences on vigilant behavior. He pointed out that, when the organism is deprived of sensory input or the latter is sharply curtailed, the activity of the waking center is reduced and the organism lapses into a state of sleep. However, wakefulness of choice, the autonomous activity of the cortex, can exercise control over sleep-wakefulness behavior.

This interpretation of the mass action findings in terms of a neurophysiological mechanism is admittedly speculative; nevertheless, it explains why tests of psychological vigilance, which reflect variations in conscious awareness, correlate with size of lesion. Hebb agrees that

when hypersynchrony is not too widespread it would primarily affect these functions while leaving old learned patterns relatively undisturbed: "When hypersynchrony is not great, it would allow some assemblies to function (particularly those that are well established) but would tend to interfere with recent memory, decrease responsiveness, and interfere with complex intellectual activities. When it is more extensive, it would prevent all higher function" (**24**, p. 283).

It is probably not without significance that the "dull and sleepy" reactions noted by Landis et al. (**30**) in their lobotomy and lobectomy studies occur during the period after cortical operations when most patients show definite abnormalities in EEG rhythm expressed as high voltage, three to seven per second delta waves.

Other clinical and experimental observations are also consistent with this proposed explanation of mass action. The decrement and variability in level of performance, especially on tests of immediate memory and new learning, have been repeatedly observed in patients with brain injury. Crawford et al (**6**) noted similar day-to-day variability in the level of performance of chimpanzees with brain lesions. Occasional peaks in performance, however, are precisely what one might anticipate under conditions which may reduce or temporarily eliminate the hypersynchrony induced by lesions which partially deafferent the cortex. With heightened interest or intensity of experience, as under increased motivation or emotional involvement, the afferent influx to the cortex may increase sufficiently to compensate for the nonspecific sensory support which is lost or reduced as a result of tissue removal.

Interestingly, this same variability of behavior in patients with cortical lesions has been used to argue that tissue disturbance rather than tissue deficit must be responsible for the losses reported. If behavior can at times rise to preoperative levels, it indeed appears difficult to explain how variable impairment can be assigned to absent cortex rather than to the tissue which remains. It should be clear from the discussion, however, that either the removal of tissue or disturbed functioning of remaining tissue could be responsible to the extent that either contributes to cortical hypersynchrony. As used here, tissue deficit does not imply that the function impaired by cortical excision resides in the removed tissue. The term is used to indicate that impairment is intimately related to the loss of tissue, whether this be in a primary or secondary sense, and is contrasted with losses attributed to cortical disturbances which implicate actively malfunctioning tissue as the basis for behavioral loss.

*Hemisphere Dominance*

Five tests showed a "hemisphere × area" interaction and/or a differential impairment in patients with right as compared with left hemisphere lesions. These were of statistical or borderline statistical significance. On all these tests, patients with left hemisphere lesions performed more poorly than those with right hemisphere lesions.

When the "hemisphere × area" interactions were examined further for the four tests studied by analysis of variance procedures, patients with large lesions in the left hemisphere were found to be more impaired than patients with either small lesions in the left hemisphere or large or small lesions in the right hemisphere. If these four tests were statistically independent, the odds that this phenomena would have occurred by chance are one in 256 or .004.

What, if any, single function tends to be maximally influenced by differences in the involved hemisphere is not immediately clear from the data, since the five tests which show these differences appear to vary considerably upon superficial examination. A partial suggestion emerges for two of the tests which were included in Halstead's factor analysis. The Category and Henmon-Nelson Intelligence tests both have significant factor loadings on Halstead's *C* factor. The Henmon-Nelson Intelligence Test is a paper-and-pencil, verbal test, and the Category Test demands "verbal-logical" ability for its solution. Thus, it is possible that these tests represent only one of the dimensions of the *C* factor, viz., verbal learning. Nonverbal tests of the *C* factor which are included in the present analysis fail to show any relationship to hemisphere. A factor analysis to be carried out on the same data may answer this question more definitively. Nevertheless, the findings on these two tests are in essential agreement with several studies (**2, 38, 49**) reporting greater impairment on verbal intelligence tests in patients with left than with right hemisphere lesions.

*Biological Intelligence*

The Impairment Index, a composite score calculated on the basis of critical scores on the first ten tests in the battery, is by far the most sensitive indicator in discriminating frontal from nonfrontal cases, and is the only measure to do so outside of the abstraction tests. On first sight, this finding may appear puzzling. Frontals are more impaired than nonfrontals at significant or borderline significant levels on only two of the first ten tests—Tests I and V, which are measures of abstraction. None of the other eight tests used in the index reveal mean differences between frontals and nonfrontals even approaching borderline statistical significance. Yet the mean Impairment Index score for frontals is significantly greater than that for nonfrontals and this difference is significant beyond the .001 level.

In looking for the reason behind this finding, one notes that, for nine of the ten tests contributing to the index score, frontals perform more poorly than nonfrontals, although the mean difference between these groups approaches statistical significance for only the two abstraction tests. A summation of these findings, which are below statistically significant levels for most of the individual tests, apparently results in an index which differentiates frontals from nonfrontals at this high level of significance. The findings for the index suggest that the character of psychological loss following frontal lobectomy is not unitary, but probably extends into a number of dimensions of behavior as Halstead suggests in his concept of "biological intelligence."

Following excisions of frontal lobe tissue, impairment almost invariably extends beyond that involved in abstraction ability. This becomes apparent from the indices in Table 1 through 8 of appendix A. Only 3 of the 34 frontal lobectomy patients on whom index scores were calculated have an Impairment Index below 0.5, whereas 20 of the 35 nonfrontal cases have indices below 0.5. Furthermore, all 3 of the frontal cases with indices below 0.5 involve the smallest amounts of tissue removal. In addition, in 2 of these cases the tissue removed was primarily from the precentral gyrus, and in the third, from the posterior parolfactory sulcus and subcallosal gyrus. Thus in all three instances, the large prefrontal areas were relatively uninvolved by the lesions.

One can thus expect impairment in more than one area of "biological intelligence" following frontal lobectomy, but apart from the greater likelihood of loss in abstraction, the specific functions impaired may be expected to vary in different individuals. The varying nature of this loss will in part reflect the hemisphere and size of the lesion; however, the indications of unique configurations of loss for patients with lesions of comparable size in similar quadrants indicate that variability of loss is only partially accounted for by the latter factors.

The findings with respect to the importance of locus, plus the fact that hemisphere and size of lesion are unrelated to scores on the Impairment Index, clearly lend support to Halstead's use of this measure as an indicator of frontal lobe lesions.

*Additional Findings*

Only one of the 15 measures correlates significantly with age, and this is within the limits of chance expectation for this number of correlations. As a result, it cannot be accorded any special significance unless cross-validated on another group. These results affirm Halstead's belief that his tests are but minimally influenced by this variable.

Tests V and VI, because of their loading on Halstead's *A* and *P* factors, were treated as measures involving both psychological vigilance and abstraction. (Test V, which has a sizeable loading on the *A* factor, was also analzyed separately as a measure of abstraction.) Since psychological vigilance tests are related to size of lesion, and abstraction tests are differentially impaired by lesions in the frontal and nonfrontal areas, a test combining these two functions might be expected to reflect both of these relationships in combined form. The significant and borderline significant *F* ratios for the "area × locus" interaction for Tests V and VI respectively are in accord with this expectation. The relative sizes of the two *F* ratios for the interaction terms are also consistent with the sizes of the factor loadings for these tests on the *A* and *P* factors in Halstead's study.

A number of other interesting relationships between the cortical lesion dimensions and test performance have been summarized in the results section. Until the nature of the demands in some of these tests is more clearly understood, however, little would appear to be gained by attempting to specify their representation in the cortex. With further investigation of these tests in future localization studies and in analyses of the behavioral functions they involve, these findings may take on more critical significance.

*Implications for Halstead's Four-Factor Theory*

In discussing his theory of "biological intelligence," Halstead made the following observations:

> It is extremely unlikely that our ultimate conception of the structure of biological intelligence will be satisfied with the four-factor space projected here. It seems highly probable to the writer, however, that the four factors which we have isolated with the present battery are truly reflectors of brain functions. In this sense they are basic or planetary factors. But is it not reasonable to expect that, as we refine our indicators and develop additional ones, we will in time locate satellites and asteroids for each of the planetary factors? At such time our conception of ego structure will require *n*-factor space for its complete description (**17**, pp. 95-96).

The present study has explored further Halstead's theory by examining the differential representation of his factors in the cortex. In line with Halstead's expectations, some shifts in the meaning of his factors have emerged which suggest some directions for further refining his

model of "biological intelligence."

The findings for the *A* factor and the Impairment Index confirm Halstead's earlier conclusions. The abstraction tests and the index are primarily impaired by frontal lobe lesions as compared with lesions in the nonfrontal areas. The discovery of the importance of size of lesion within the frontal lobes for the impairment of the *A* factor suggests a mass action influence in addition to the regional localization of this factor.

Two tests of the *C* factor calling for verbal and symbol manipulation demonstrate a relationship to laterality of lesion which nonverbal *C* factor tests do not show. This fact suggests that the *C* factor may be capable of further breakdown.

It has been suggested that variations in consciousness and their reflections in measures of immediate memory are more intimately related to the *P* than to the *C* factor. Halstead's interpretation of his *P* factor as that which "operates to counterbalance or regulate affective forces" is not inconsistent with the definition of the *P* factor in terms of psychological vigilance. Lindsley (**36**) also has suggested that the same system which is involved in determining the levels of conscious awareness may well be the energizer in emotional behavior.

In the experiment of Doust and Schneider (**7**), in which oximetric anoxaemia or hyperoxaemia was produced by intermittent sensory stimulation at critical frequencies, those oxygen levels which were accompanied by alterations in conscious awareness were also accompanied by alterations in emotionality. At low oxygen levels, normal subjects became irritable and aggressive; neurotic patients became frightened, with sweating, cringing, and pallor; and psychotic patients reported hallucinations, became suspicious, and showed other evidences of overt anxiety. When critical stimulation frequencies were increased, and oxygen levels rose to resting values, these phenomena disappeared.

Here we have a dramatic demonstration that the regulation of affective forces is intimately tied up with variations in level of conscious awareness. The procedure of intermittent sensory stimulation by which these emotional phenomena are produced is also closely related to the CFF test which is the best measure of the *P* factor. The reinterpretation of the *P* factor, then, implies a shift in emphasis rather than a basic alteration from its previous meaning.

Perhaps the most promising finding of the present study is that the distinctiveness in function which has been emphasized on the basis of factor analysis is paralleled by the differential localization in the cortex of three of Halstead's four factors. Data were not adequate to appraise the localization of the fourth factor. These findings demonstrate rather vividly the reciprocal reinforcement and complementary character of factor analysis and cerebral localization studies for the development of a neuropsychological model of cortical functioning.

## Summary and Conclusions

This research was designed to study the relationship between size and location of excised cortex and impairment of intellectual functions in man.

Patients included in the study were treated for removal of tumors, abscesses, epileptogenic foci, and scar tissue, involving unilateral excisions of cortical tissue in either the frontal or nonfrontal areas. Sketches of the surgical lesions were obtained on standard charts which allowed for quantitative estimates of the extent of the excisions as well as their localization. Lesions were classified for three di-

mensions: location, frontal or nonfrontal; hemisphere, right or left; and size, large or small removals. Eight groups, with six or more patients each, represented all possible combinations of these three dimensions. These eight groups were not statistically different from each other with respect to age and a time index representing the time interval between surgery and testing. The relationship of location, hemisphere, and size of lesion to test performance was appraised by triple-classification analysis of variance for most of the tests.

The patients were studied postoperatively on a battery of 15 tests including measures of three of Halstead's four factors of "biological intelligence" and his Impairment Index. These measures were selected because of their demonstrated sensitivity in revealing the presence of lesions in the cortex. In addition to the above analysis, test scores were also correlated with size of lesion, age, and the time index. The following conclusions are warranted on the basis of the findings:

1. No specific intellectual process is localized in any cortical area such that a loss of function invariably follows removal of that region. However, the various cortical areas are of decidedly unequal importance for the mediation of various intellectual functions.

2. Patients with frontal lobe excisions perform more poorly on almost all tests; however, this difference is statistically significant only on abstraction (*A* factor) tests and Halstead's Impairment Index.

3. In frontal cases, size of lesion is significantly related to impairment of abstraction ability. Nonfrontal cases do not show this relationship. This finding suggests a mass action influence within the frontal lobes for this function.

4. Abstraction ability is not significantly more impaired by lesions in one hemisphere than in the other.

5. The findings for the Impairment Index demonstrate that frontal lobe lesions are always accompanied by loss extending into a number of areas of "biological intelligence," but that aside from a greater likelihood of impairment in the *A* factor, the specific functions impaired vary in different individuals.

6. Tests of the *C* factor, dealing with verbal-logical ability, show greater impairment with left- than with right-sided lesions.

7. Tests of psychological vigilance which reflect small variations in level of conscious awareness are all significantly related to size, but not to locus, of lesion.

8. The same tests of psychological vigilance are the only measures correlating significantly with the time index. The latter, being an index of the time interval between surgery and testing, indicates that the temporal course of postoperative recovery of the cortex from the surgical trauma is also correlated with psychological vigilance.

9. A neurophysiological mechanism is proposed to explain the mass action and time-index findings for tests of psychological vigilance. An attempt is made to relate the amount of tissue excised to proportionate reductions in nonspecific afferent support of the cortex which in turn influences the level of conscious awareness.

10. There is no clear evidence that nonfrontal cases treated for removal of epileptogenic foci and scar tissue differ significantly in test performances from nonfrontal cases treated for removal of tumors and other conditions which presumably involve a greater likelihood of widespread cortical involvement.

11. The findings do not appear to be attributable to differences in age or to the incidence of malfunctioning tissue among the eight groups.

12. The differential cortical localization of the three factors studied affirms their uniqueness as established previously in Halstead's factor analysis.

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*(Accepted for publication September 25, 1957.)*

## APPENDIX A

### CRITERION SCORES

| | Test Indicators | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X |
| Criterion Score | >50 | <21.0 | <.7 | >15.6 | <6 | <5 | >5 | >7 | <51 | >260 |

Note.—The criterion scores in this table were used in calculating each patient's Impairment Index. For those test scores greater than a criterion score preceded by ">" or less than a criterion score preceded by "<," 0.1 is added to the Index.

# APPENDIX B

## TABLE 1

GROUP A. LEFT NONFRONTAL SMALL LESION TEST SCORES AND LESION ESTIMATES

| Case No. | Test Indicators | | | | | | | | | | | | | | | % Lesion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | XIII | XIV | XV | |
| 1 | 46 | 16.0 | 1.2 | 27.6 | 5 | 0 | 10 | 9 | 54 | 143 | 353 | 56 | — | — | 0.6 | 1.5 |
| 2 | — | 19.1 | 1.2 | 14.7 | 7 | 5 | — | — | 54 | 176 | — | 20 | — | — | 0.1 | 2.8 |
| 3 | — | — | — | 33.3 | 7 | 1 | — | — | 24 | 14 | 44 | — | — | 97 | 0.6 | 3.1 |
| 4 | — | 26.0 | 1.3 | 19.7 | 8 | 7 | — | — | 36 | 150 | — | 21 | — | — | 0.3 | 3.9 |
| 5 | — | 23.0 | 1.2 | — | — | — | — | — | — | — | — | — | — | — | — | 4.8 |
| 6 | 35 | 17.2 | 0.4 | 22.8 | 6 | 0 | 1 | — | 48 | 886 | 51 | 39 | 64 | 96 | 0.7 | 5.4 |
| 7 | 52 | 25.5 | 1.3 | 14.1 | 8 | 8 | 10 | 6 | 41 | 135 | 57 | — | 95 | 126 | 0.3 | 5.6 |
| 8 | 18 | 22.2 | 0.5 | 14.0 | 8 | 1 | 1 | 5 | 42 | 293 | 41 | — | 99 | 135 | 0.4 | 5.6 |
| 9 | 74 | 29.5 | 0.9 | 21.8 | 8 | 5 | 3 | 4 | 41 | 216 | 53 | — | 82 | 111 | 0.3 | 5.9 |
| 10 | 20 | 27.5 | 0.9 | 9.8 | 9 | 6 | 6 | 1 | 56 | 515 | 12 | — | 97 | 126 | 0.2 | 6.0 |
| 11 | 38 | 18.8 | 0.5 | 9.8 | 8 | 3 | 3 | 16 | 41 | 236 | 50 | — | 79 | 128 | 0.5 | 6.0 |
| 12 | — | 23.2 | 1.3 | — | — | — | — | — | — | — | — | — | — | — | — | 6.1 |

## TABLE 2

GROUP B. RIGHT NONFRONTAL SMALL LESION TEST SCORES AND LESION ESTIMATES

| Case No. | Test Indicators | | | | | | | | | | | | | | | % Lesion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | XIII | XIV | XV | |
| 21 | 67 | 19.9 | 0.4 | 18.0 | 6 | 1 | 1 | 10 | 47 | 193 | 20 | 13 | 100 | 97 | 0.7 | 3.1 |
| 22 | 85 | 22.8 | 0.8 | 42.7 | 3 | 1 | 7 | — | 20 | 846 | 106 | — | — | 87 | 0.7 | 3.1 |
| 23 | 46 | 22.0 | 0.5 | 18.4 | 5 | 4 | 6 | 2 | 34 | 149 | 142 | 43 | — | 105 | 0.6 | 4.3 |
| 24 | — | 26.2 | 1.5 | 13.3 | 8 | 7 | — | — | 39 | 187 | — | 38 | — | — | 0.1 | 4.4 |
| 25 | 60 | 20.3 | 1.1 | 29.6 | 5 | 1 | 10 | 15 | 48 | 470 | 17 | 46 | 85 | 96 | 0.9 | 5.0 |
| 26 | 7 | 24.3 | 0.6 | 10.3 | 9 | 5 | 3 | 4 | 42 | 693 | 49 | — | 104 | 135 | 0.3 | 5.0 |
| 27 | 12 | 23.7 | 0.4 | 10.0 | 9 | 5 | 3 | 6 | 47 | 344 | 13 | — | 114 | 144 | 0.3 | 5.1 |
| 28 | 47 | 24.5 | 0.9 | 13.3 | 8 | 5 | 10 | 8 | 56 | 361 | 76 | — | 92 | 113 | 0.3 | 5.2 |
| 29 | 18 | 21.5 | 0.8 | 9.0 | 8 | 6 | 6 | 3 | 46 | 179 | 117 | — | 101 | 100 | 0.2 | 5.4 |
| 30 | 74 | 20.2 | 0.4 | 17.3 | 7 | 6 | 6 | 13 | 46 | 662 | 20 | — | 57 | 79 | 0.8 | 5.9 |
| 31 | 65 | 20.0 | 0.8 | 23.1 | 3 | 0 | 5 | 18 | 31 | 370 | 53 | — | 53 | 106 | 0.8 | 6.0 |

## TABLE 3

GROUP C. RIGHT NONFRONTAL LARGE LESION TEST SCORES AND LESION ESTIMATES

| Case No. | Test Indicators | | | | | | | | | | | | | | | % Lesion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VI | VIII | IX | X | XI | XII | XIII | XIV | XV | |
| 41 | — | 12.6 | 0.2 | — | — | — | — | — | 51 | 143 | — | 15 | 110* | — | 0.5 | 33.0 |
| 42 | — | 12.6 | 1.8 | 11.7 | 7 | 5 | — | — | 52 | 481 | — | 17 | 91* | — | 0.3 | 15.6 |
| 43 | 38 | 21.3 | 0.3 | 9.9 | 7 | 6 | 6 | 3 | 53 | 909 | 18 | — | 114 | 118 | 0.3 | 12.4 |
| 44 | 28 | 17.3 | 1.0 | 10.8 | 8 | 4 | 3 | 7 | 52 | 139 | 87 | 26 | 121 | 104 | 0.2 | 11.9 |
| 45 | 36 | 27.5 | 0.9 | 48.9 | 3 | 2 | 8 | 8 | 56 | 313 | 18 | — | 84 | 86 | 0.6 | 10.9 |
| 46 | 20 | 18.0 | 0.6 | 14.3 | 8 | 3 | 2 | 2 | 48 | 233 | 25 | — | 124 | 114 | 0.4 | 9.8 |
| 47 | — | 24.3 | 1.1 | 13.2 | 8 | 6 | — | — | 57 | 391 | — | 19 | — | — | 0.1 | 6.8 |

* Based on Stanford-Binet or Wechsler-Bellevue IQs.

TABLE 4

GROUP D. LEFT FRONTAL LARGE LESION TEST SCORES AND LESION ESTIMATES

| Case No. | Test Indicators | | | | | | | | | | | | | | | % Lesion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | XIII | XIV | XV | |
| 51 | — | 14.8 | 0.2 | 23.5 | 4 | 2 | — | — | 41 | 255 | — | 43 | — | — | 0.9 | 16.0 |
| 52 | 140 | — | — | 53.0 | 0 | 0 | 10 | 8 | 34 | 722 | 502 | — | 60* | — | 1.0 | 14.4 |
| 53 | 45 | 18.8 | 1.4 | 22.8 | 6 | 3 | 10 | 10 | 64 | 621 | 31 | 56 | 94 | 44 | 0.6 | 13.6 |
| 54 | 81 | 23.8 | 3.0 | 53.0 | 4 | 3 | 5 | 11 | 30 | 199 | 309 | 57 | 73 | — | 0.6 | 11.8 |
| 55 | — | 19.2 | 0.3 | — | — | — | — | — | — | — | — | — | — | — | — | 11.7 |
| 56 | — | 14.4 | 0.5 | 28.3 | 3 | 1 | — | — | 41 | 581 | — | 39 | — | — | 1.0 | 11.5 |
| 57 | 82 | 13.8 | 0.3 | 13.3 | 7 | 7 | 10 | 9 | 45 | 321 | 175 | 48 | 74 | 89 | 0.7 | 11.2 |
| 58 | — | — | — | 23.1 | 4 | 0 | — | — | 32 | 1584 | 238 | — | — | — | 1.0 | 7.3 |
| 59 | — | 18.6 | 0.4 | 19.2 | 5 | 3 | — | — | 41 | 310 | — | — | — | — | 1.0 | 6.5 |

* Based on either Stanford-Binet or Wechsler-Bellevue IQs.

TABLE 5

GROUP E. RIGHT FRONTAL LARGE LESION TEST SCORES AND LESION ESTIMATES

| Case No. | Test Indicators | | | | | | | | | | | | | | | % Lesion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | XIII | XIV | XV | |
| 61 | 26 | 22.2 | 0.6 | 26.2 | 6 | 3 | — | 13 | 46 | 1220 | 99 | — | 71 | 83 | 0.7 | 19.5 |
| 62 | 60 | 20.2 | 0.7 | 29.5 | 2 | 0 | 10 | 17 | 50 | 377 | 32 | 56 | 89 | 80 | 0.9 | 18.2 |
| 63 | 57 | 18.8 | 0.6 | 37.1 | 6 | 4 | 10 | 12 | 46 | 141 | 91 | — | 64 | 77 | 0.8 | 17.7 |
| 64 | 70 | 18.0 | 0.6 | 23.3 | 7 | 4 | 3 | 7 | 49 | 1556 | 47 | 36 | 101 | 79 | 0.7 | 14.1 |
| 65 | — | 14.2 | 0.8 | — | — | — | — | — | 37 | 19 | 228 | — | — | — | 0.5 | 13.1 |
| 66 | — | 22.6 | 1.1 | 19.4 | 3 | 2 | — | — | 48 | 162 | — | 42 | — | — | 0.6 | 12.0 |
| 67 | 84 | 21.2 | 1.3 | — | — | — | — | — | 46 | 977 | 446 | — | — | — | 0.6 | 11.5 |
| 68 | 128 | 21.3 | 1.0 | 30.3 | 7 | 2 | 2 | 2 | 38 | 270 | 124 | — | 96 | 72 | 0.5 | 10.6 |
| 69 | 47 | 16.2 | 0.9 | 26.6 | 8 | 3 | 8 | 7 | 45 | 366 | 186 | — | 78 | 90 | 0.6 | 8.0 |
| 70 | — | 18.2 | 0.3 | 15.0 | 5 | 4 | — | — | 50 | 451 | — | 38 | — | — | 0.7 | 7.2 |

TABLE 6

GROUP F. LEFT FRONTAL SMALL LESION TEST SCORES AND LESION ESTIMATES

| Case No. | Test Indicators | | | | | | | | | | | | | | | % Lesion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | XIII | XIV | XV | |
| 71 | 47 | 21.0 | 0.5 | 11.1 | 9 | 8 | 5 | 4 | 46 | 332 | 152 | — | 110* | — | 0.3 | 0.6 |
| 72 | 56 | 21.2 | 1.1 | 13.8 | 6 | 1 | 1 | 4 | 47 | 224 | 18 | — | 115* | — | 0.3 | 1.2 |
| 73 | 67 | 15.8 | 0.4 | 53.0 | 4 | 0 | 5 | 10 | 49 | 381 | 33 | 51 | 57 | 97 | 0.9 | 1.2 |
| 74 | 62 | 17.2 | 0.3 | 8.5 | 6 | 3 | 5 | 9 | 40 | 157 | 125 | 34 | 86 | 102 | 0.6 | 2.4 |
| 75 | — | 20.1 | 0.6 | 23.0 | 5 | 2 | — | — | 46 | — | — | 19 | — | — | 1.0 | 2.6 |
| 76 | — | 20.3 | 0.3 | 28.0 | 3 | 1 | — | — | 44 | 642 | — | 37 | 110* | — | 1.0 | 3.5 |
| 77 | 55 | 19.5 | 0.6 | 23.5 | 5 | 1 | 2 | 2 | 56 | 131 | 81 | — | 75 | 95 | 0.6 | 3.6 |
| 78 | 51 | 27.0 | 0.3 | 11.4 | 6 | 3 | 8 | 8 | 48 | 104 | 41 | — | 102 | 98 | 0.6 | 3.8 |
| 79 | — | 17.6 | 0.2 | 21.3 | 6 | 4 | — | — | 39 | 417 | — | 21 | — | — | 0.9 | 6.1 |
| 80 | — | 20.1 | 0.3 | 17.0 | 6 | 3 | — | — | 45 | — | — | 18 | — | — | 0.8 | 1.7** |

* Based on Stanford-Binet or Wechsler-Bellevue IQs.

** Subject 80 was included in the study after the analysis of variance procedure was completed and was used only in the correlational analysis.

TABLE 7

GROUP G. RIGHT FRONTAL SMALL LESION TEST SCORES AND LESION ESTIMATES

| Case No. | Test Indicators | | | | | | | | | | | | | | | % Lesion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | XIII | XIV | XV | |
| 81 | 48 | 27.6 | 3.6 | 14.6 | 5 | 4 | 2 | 11 | 51 | 173 | 31 | 23 | 137* | 110 | 0.3 | 0.5 |
| 82 | 61 | 15.1 | 0.3 | — | — | — | 10 | — | 45 | 774 | 120 | 47 | 88 | 85 | 1.0 | 1.2 |
| 83 | 45 | 17.5 | 1.1 | 11.6 | 6 | 4 | 8 | 8 | 61 | 296 | 78 | 51 | 94 | 116 | 0.5 | 1.3 |
| 84 | — | 17.4 | 0.9 | 20.6 | 8 | 7 | — | — | 47 | 342 | 182 | — | 92 | 101 | 0.6 | 2.3 |
| 85 | 39 | 20.8 | 0.0 | 18.4 | 8 | 4 | 6 | 5 | 56 | 623 | 45 | 41 | 106 | 106 | 0.6 | 2.5 |
| 86 | — | 17.3 | 0.4 | 19.4 | 5 | 3 | — | — | 53 | 206 | — | 41 | — | — | 0.7 | 4.3 |

* Based on either Stanford-Binet or Wechsler-Bellevue IQs.

TABLE 8

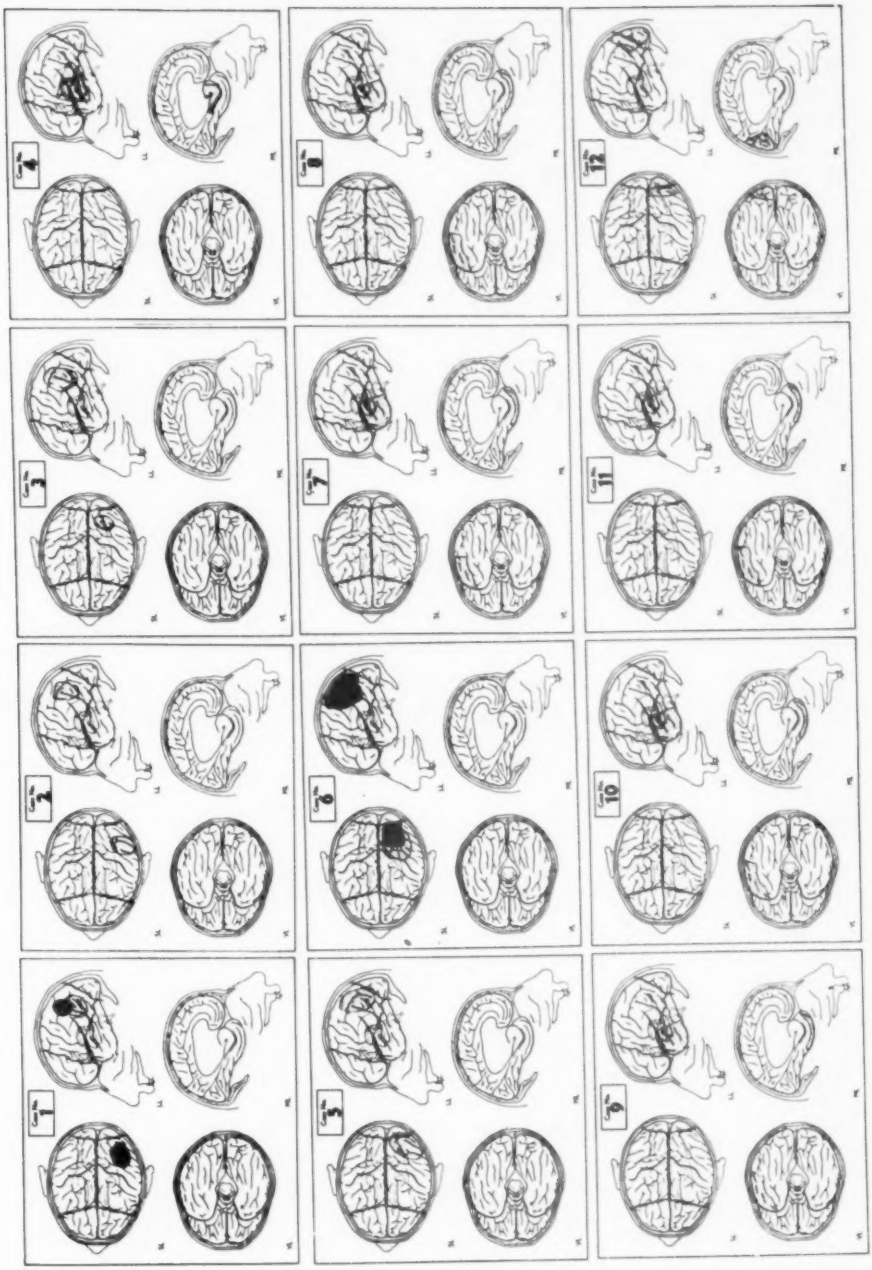
GROUP H. LEFT NONFRONTAL LARGE LESION TEST SCORES AND LESION ESTIMATES

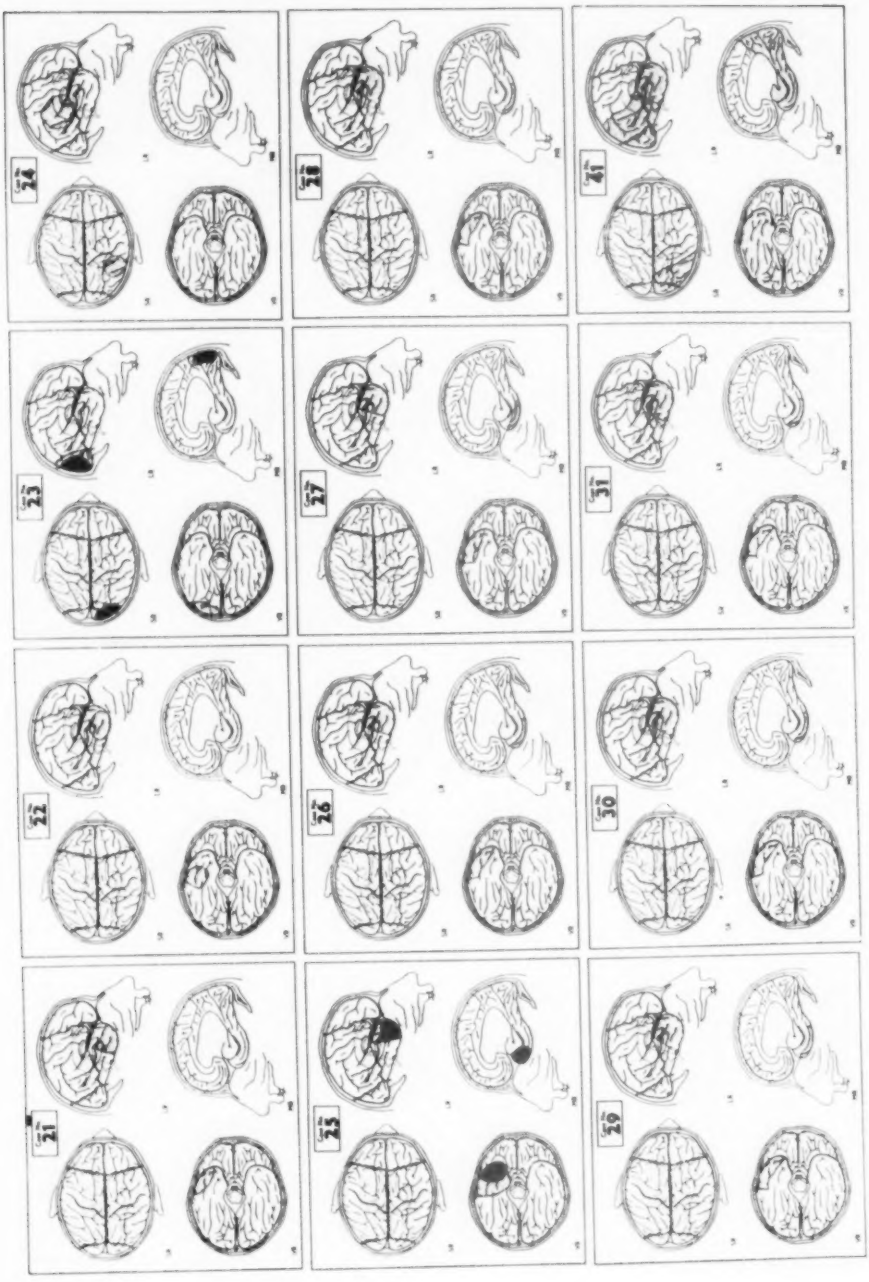
| Case No. | Test Indicators | | | | | | | | | | | | | | | % Lesion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VII | IX | X | XI | XIII | XIII | XIV | XV | |
| 91 | 123 | 14.8 | 1.0 | 46.3 | 6 | 1 | 10 | 13 | 16 | 1024 | 339 | 60 | — | 78 | 0.8 | 16.3 |
| 92 | — | 18.5 | 0.4 | 12.0 | 7 | 4 | 9 | 16 | 48 | 357 | 117 | 45 | — | 117 | 0.8 | 11.8 |
| 93 | 68 | 24.3 | 1.0 | 13.1 | 7 | 5 | 9 | 5 | 69 | 241 | 138 | 43 | 72 | 80 | 0.2 | 11.8 |
| 94 | — | 17.2 | 1.4 | 13.4 | 8 | 8 | — | — | 46 | 172 | — | 16 | — | — | 0.3 | 9.7 |
| 95 | 23 | 24.2 | 1.2 | 12.6 | 7 | 4 | — | 10 | 43 | 305 | — | 26 | — | — | 0.4 | 9.0 |
| 96 | 51 | 17.3 | 0.9 | 32.3 | 4 | 1 | 10 | 9 | 46 | 276 | 134 | — | 58 | 114 | 0.9 | 7.2 |
| 97 | 18 | 20.2 | 0.6 | 10.1 | 9 | 6 | 10 | 15 | 52 | 228 | 24 | 40 | 75 | 83 | 0.4 | 6.6 |

## Appendix C

## DIAGRAMS OF BRAIN LESIONS OF CEREBRAL LOBECTOMIES

Diagrams of the cerebral lesions for each of the 72 patients in the study are presented in the following six plates. For a description of the method employed in preparing the diagrams, see the section on "Specification of the Lesion" and Halstead's original paper (**16**). The diagrams present the cortex and lesions from superior, inferior, medial, and lateral views. Excised cortical tissue is indicated by stipling. Where stipling and crosshatching are both present in a diagram, they represent the lesion as independently visualized by two different neurossurgeons from operative notes and laboratory reports.

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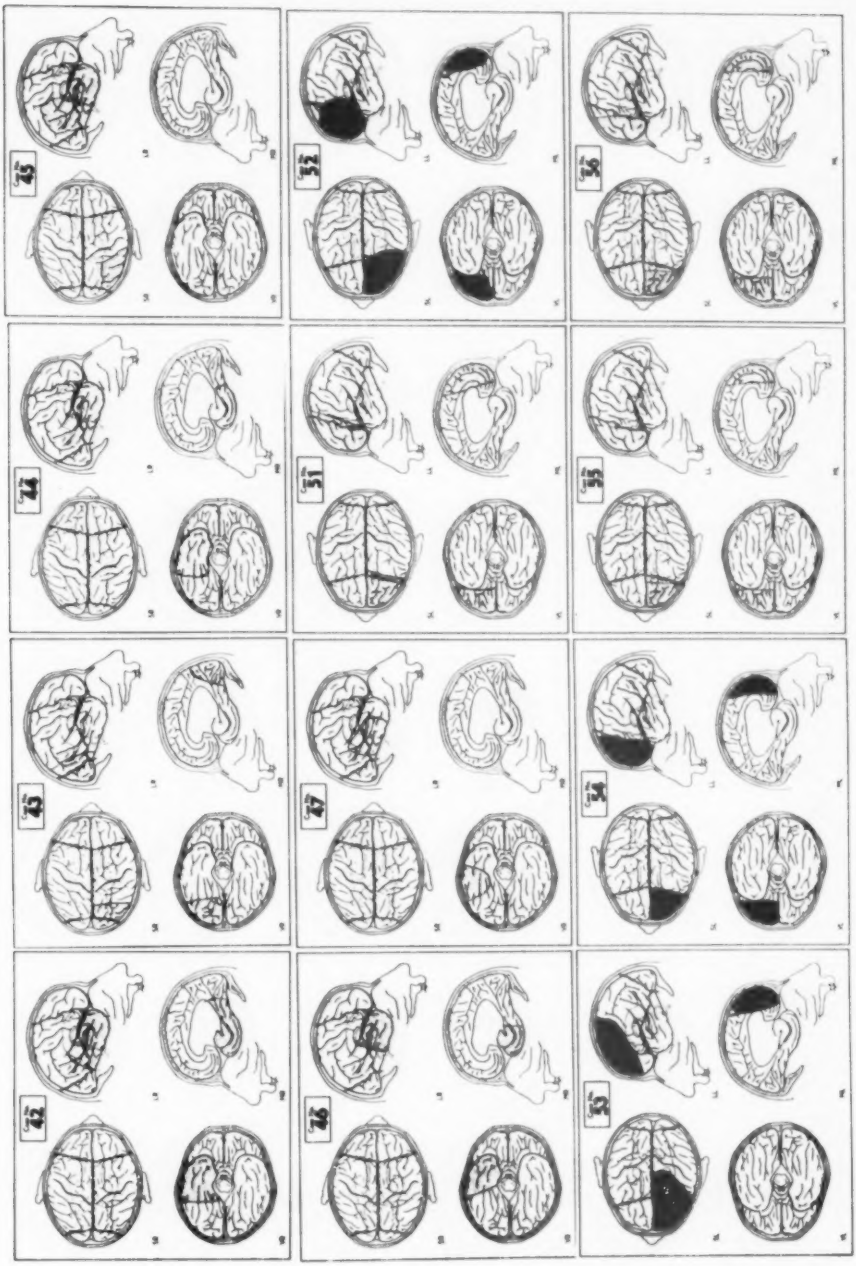
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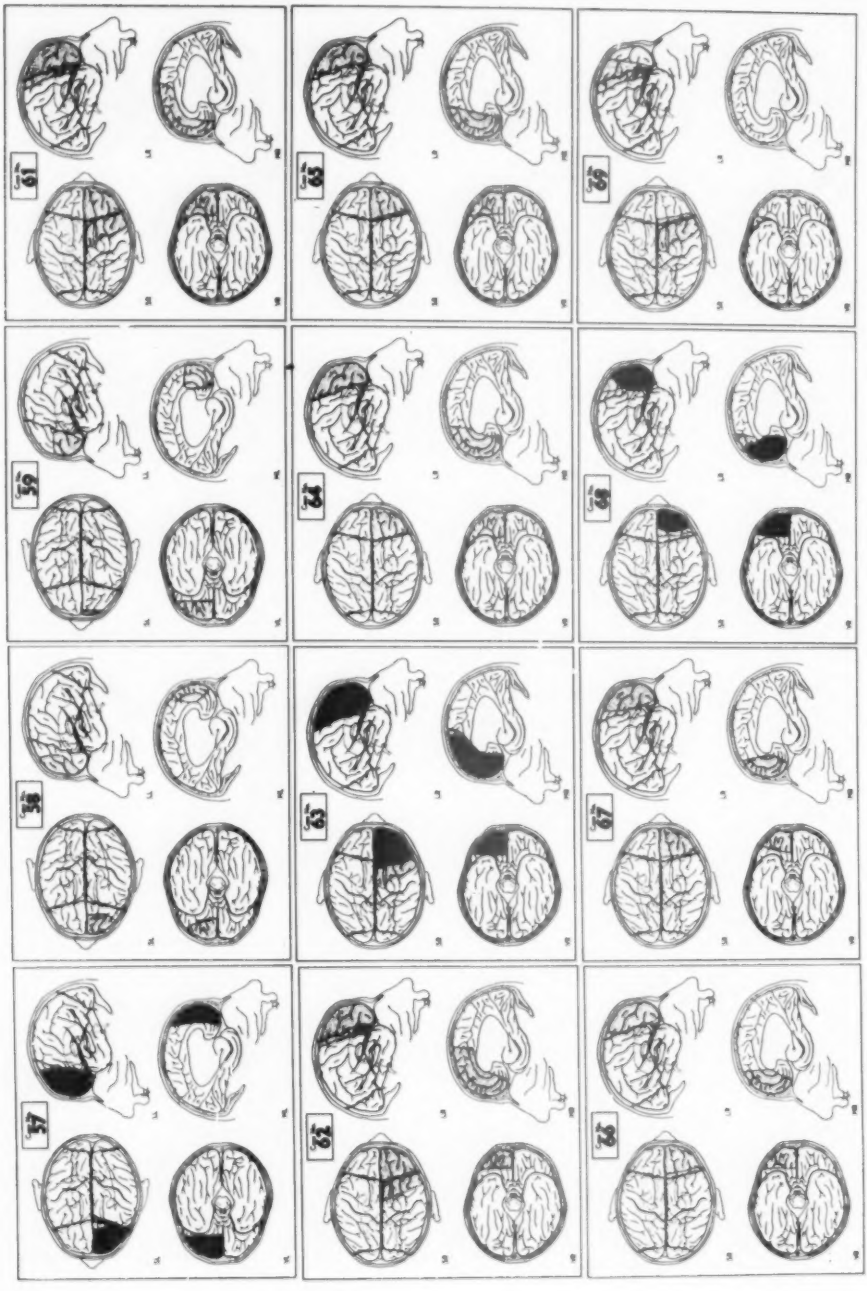

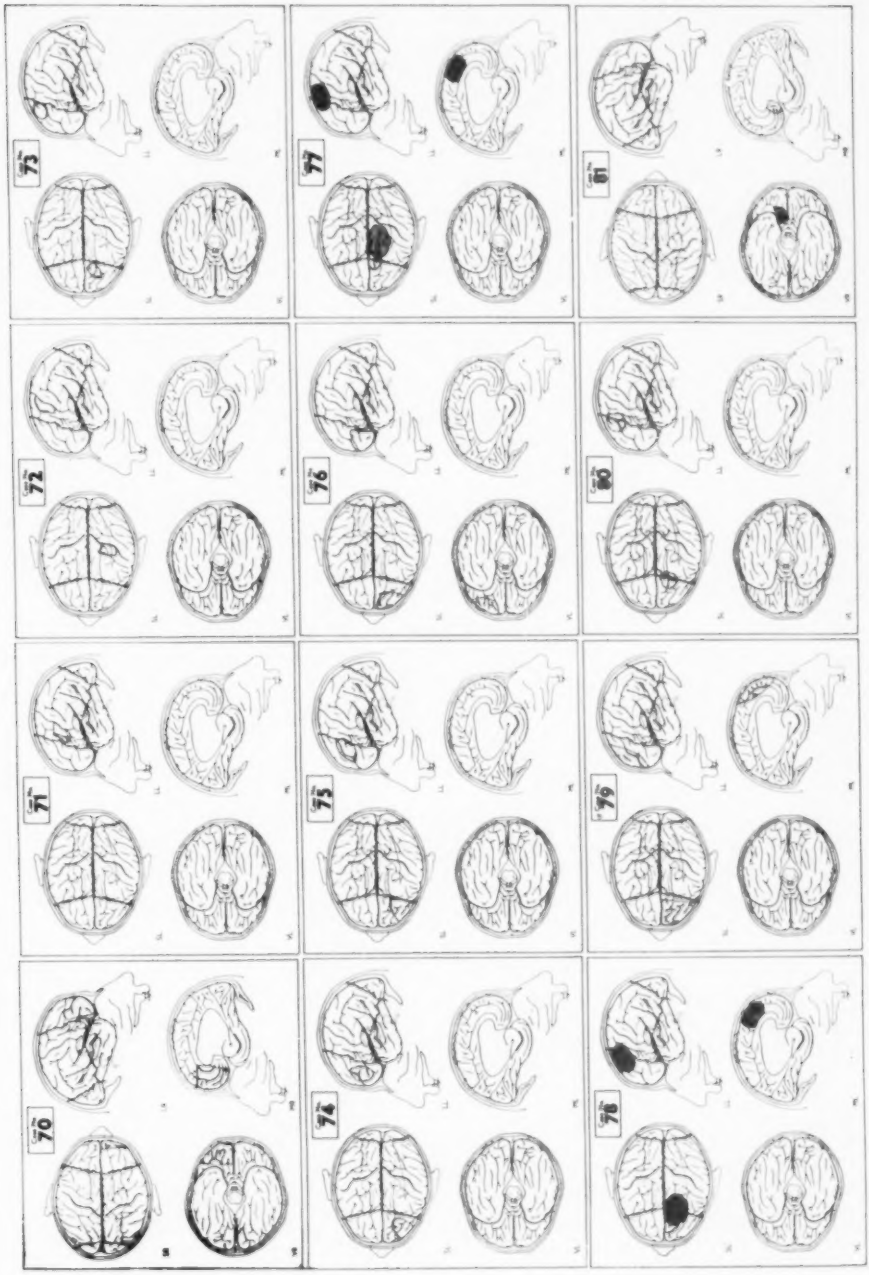
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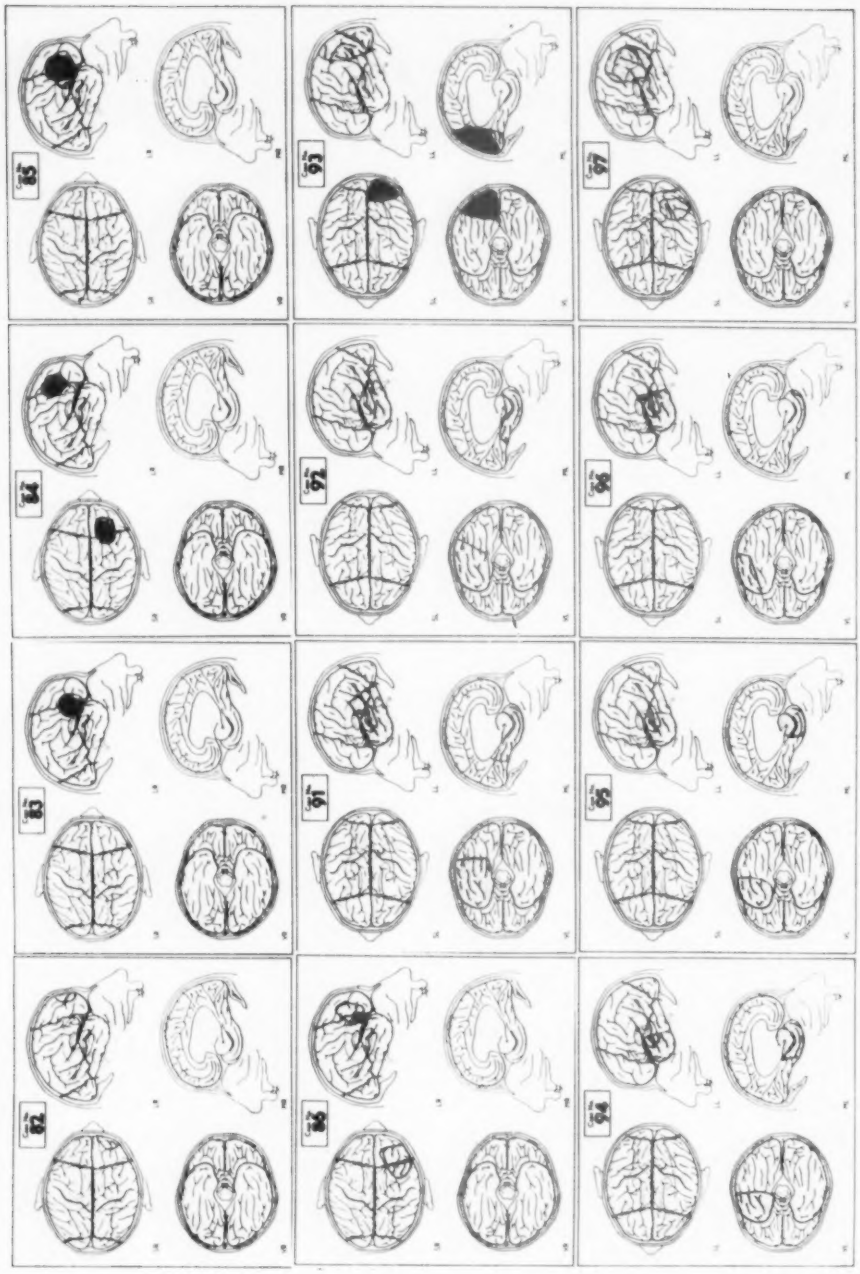

GEORGE BANTA COMPANY, INC., MENASHA, WISCONSIN